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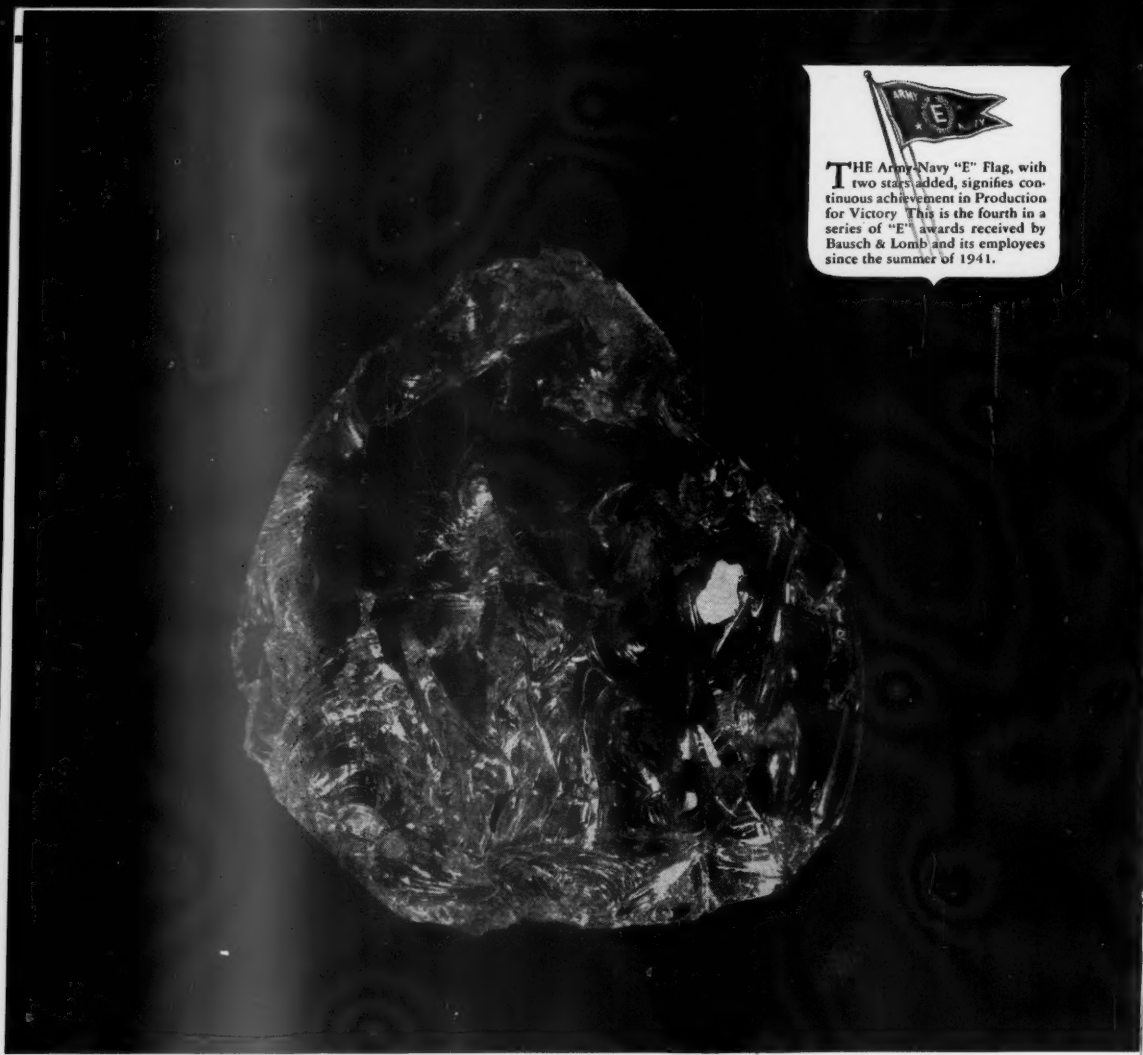

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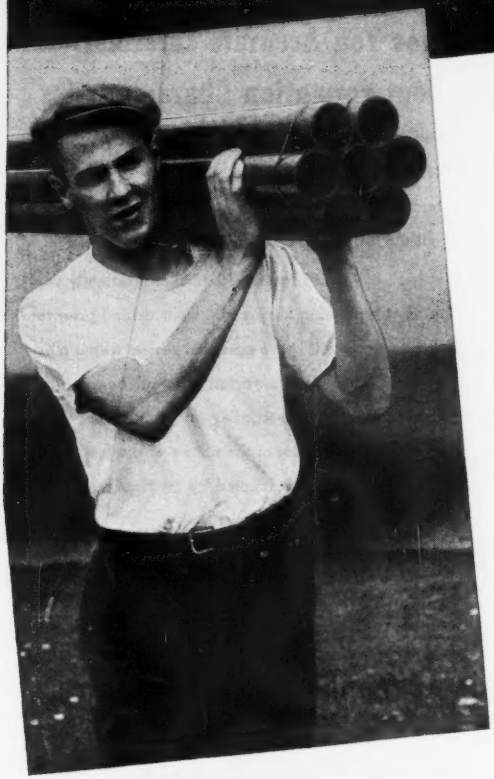

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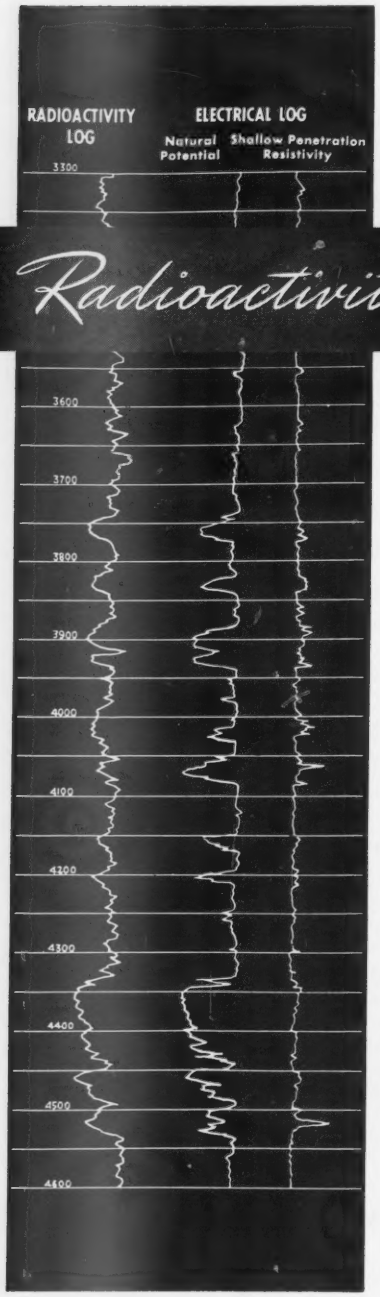

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JANUARY, 1943

EOCENE STRATIGRAPHY IN WESTERN SANTA YNEZ MOUNTAINS, SANTA BARBARA COUNTY, CALIFORNIA[1]

FREDERIC RICHARD KELLEY[2]
Stanford University, California

ABSTRACT

This paper describes the critical Eocene section at Cañada de Santa Anita, Santa Barbara County, California. The "Tejon" formation of early workers is subdivided into the Anita shale (new name), "Matilija" sandstone, "Cozy Dell" shale, Sacate formation (new name), and Gaviota formation in ascending stratigraphic order. Detailed study was confined to the Eocene strata below the type Gaviota formation. The general east-west trending anticlinal structure is complicated by strike faulting. Foraminifers in the Anita shale, which is disconformable on Cretaceous beds, suggest a middle Eocene age for the formation. The molluscan faunule in the "Matilija" is believed to belong in Clark and Vokes' (1936) "Transition stage" below the Tejon and above the Domengine. Of particular significance are faunules from the "Cozy Dell"; these belong in Laiming's (1940) Zones A-1 and A-2. The upper member of the Sacate formation contains a *Turritella* related to *T. variata*, the abundant Gaviota species.

INTRODUCTION

The purpose of this paper is to give the allocation of important faunules in the Eocene strata below the Gaviota formation at its type area. The report is based on detailed field work in a limited but critical area in the western Santa Ynez Mountains of Santa Barbara County, California (Fig. 1).

The region mapped is in the vicinity of Cañada de Santa Anita, where approximately 5,000 feet of Eocene rocks are well exposed. This area may be reached from U. S. Highway 101 by turning west on State Route 1 at Las Cruces and going 6 miles toward Lompoc. State Route 1 parallels the coastline 4 miles inland, and the area studied lies along the higher part of the hills between this highway and the coast. No roads and only a few trails cross this rugged and partly brush-covered area.

The base maps for field work are vertical aeroplane photographs prepared by the Fairchild Aerial Surveys, Inc., on the scale of one inch equal to 2,000 feet. A stereoscope was used frequently in the course of the work. Elevations were obtained from the Lompoc Quadrangle.

[1] Manuscript received, June 5, 1942.

[2] Department of geology.

ACKNOWLEDGMENTS

This study is a part of the Stanford University Eocene project under the direction of Hubert G. Schenck, to whom the writer is indebted for assistance in the field, office, and laboratory. Lois T. Martin is responsible for the provisional identifications of the foraminifers given in the accompanying tabulations. A. Myra Keen helped with the identification of the mollusks. Boris Laiming, in a letter to H. G. Schenck dated April 8, 1940, confirmed the allocation of the

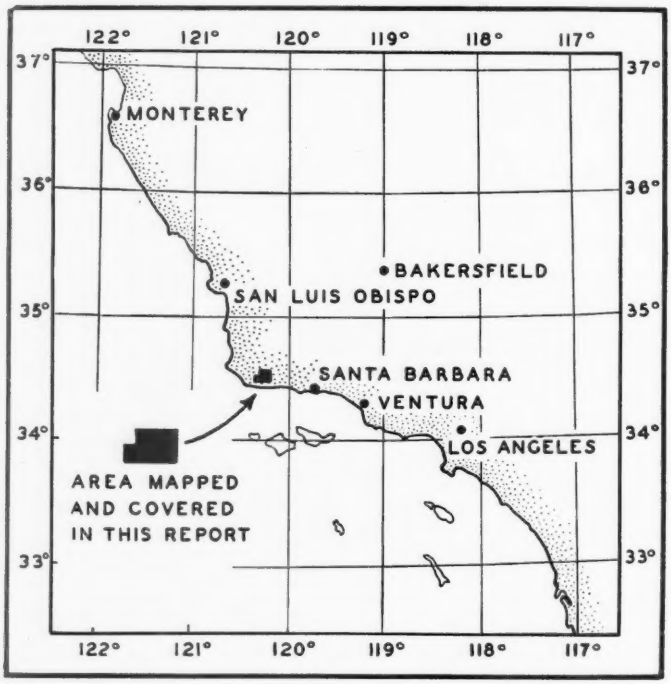

FIG. 1.—Index map of part of southern California showing location of area discussed.

faunule from Loc. M-77 to his Zone A-2. Bruce L. Clark, J. Wyatt Durham, and Charles Merriam of the University of California studied and reported on the important specimen of *Turritella* from the upper Sacate formation, and Clark identified one of the Amaurellinas from Loc. 2090. T. W. Dibblee, Jr., helped materially in the field and offered very pertinent criticism of the manuscript, as did Elmo W. Adams and Rodman K. Cross. George L. Richards, Jr., contributed valuable suggestions concerning aeroplane photographs. The many courtesies extended by T. W. Dibblee of Rancho San Julian are gratefully acknowledged.

GEOGRAPHIC SETTING

The Santa Ynez Mountains are a part of the complex of east-west-trending "transverse" ranges of southern California. The western part of the range is a region of moderately rugged relief. The regional strike of the strata parallels and determines the east-west trend of both the coastline and the range itself, and the dips of the strata are steep, in most places ranging between 45° and 90°. Normally the annual rainfall is less than 20 inches, and the rocks vary considerably in their resistance to erosion. Flowing southward, perpendicular to the main crest of the range, are many small, short, intermittent streams which drain directly downslope into the ocean. These streams have cut steep, V-shaped canyons, separated by sharp divides, in most places 500–700 feet in height. A larger stream, El Jaro Creek, drains the north side of the range, flowing northwesterly to the Santa Ynez River. Deep, differential erosion acting upon steeply dipping strata of unequal hardness accounts for the rugged, dissected character of the terrane.

The elevations vary from about 100 feet in some of the canyon bottoms to about 1,500 feet along the main divide in the western part of the area shown in Figure 2. The crest averages about 1,200 feet in elevation.

STRATIGRAPHY

Introduction.—In the western part of the Santa Ynez Mountains, paralleling the coast, there is exposed a thick Cretaceous and Tertiary section of alternating sandstone and shale units. The strata strike east and west and dip southward toward the ocean. The continuity of this section is interrupted by faulting. In the vicinity of Cañada de Santa Anita the oldest rocks are Cretaceous; overlying these are Eocene, Oligocene, and Miocene strata. This is the type area of the Gaviota formation, which was named by Effinger (1936) and further studied in this region by Schenck and Kleinpell (1936, a and b). In the present work attention was directed only to the Eocene rocks underlying the lower member of the Gaviota formation (upper Eocene) and overlying the massive Cretaceous sandstones.

The name "Tejon" has been applied to these rocks by various authors (Arnold and Anderson, 1907; Hawley, 1917; Effinger, 1936). In this report, the "Tejon" is subdivided into several cartographic units, carried in the field mapping as members, and grouped under five formational names. The generalized lithologic section follows with the formational names.

Thickness in Feet	*Lithology*	*Formational Name*	
460	Siltstone	Lower member, Gaviota formation (upper Eocene)	
1,050	Sandstone	Sacate formation (new name)	"Tejon" (Eocene)
630	Shale	"Cozy Dell"	
1,050	Sandstone	"Matilija"	
970	Shale	Anita shale (new name)	
350+	Sandstone	Upper Cretaceous	

The detailed stratigraphic section is shown in Figure 3.

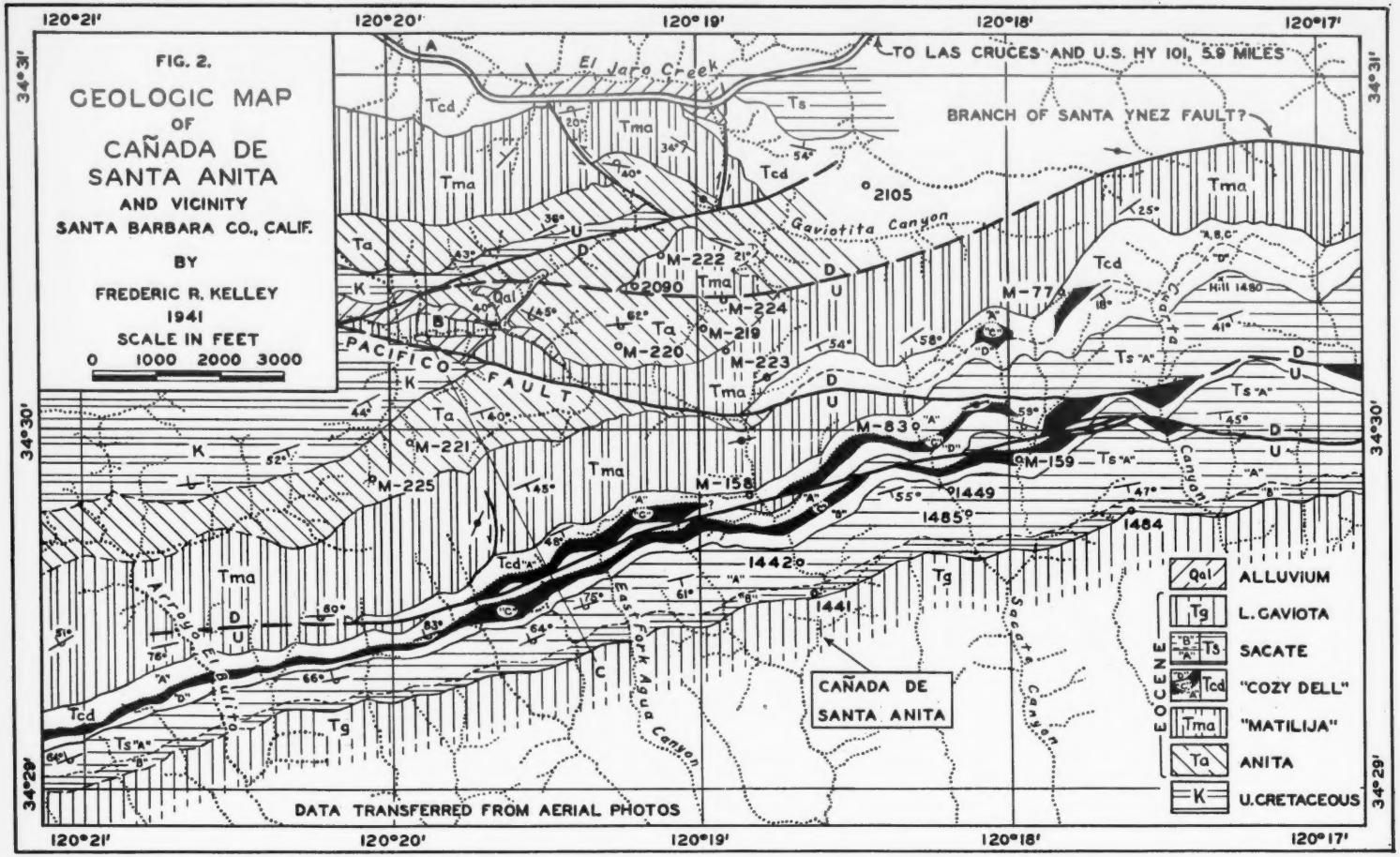

FIG. 2.—Geologic map of Cañada de Santa Anita and vicinity, Santa Barbara County, California.

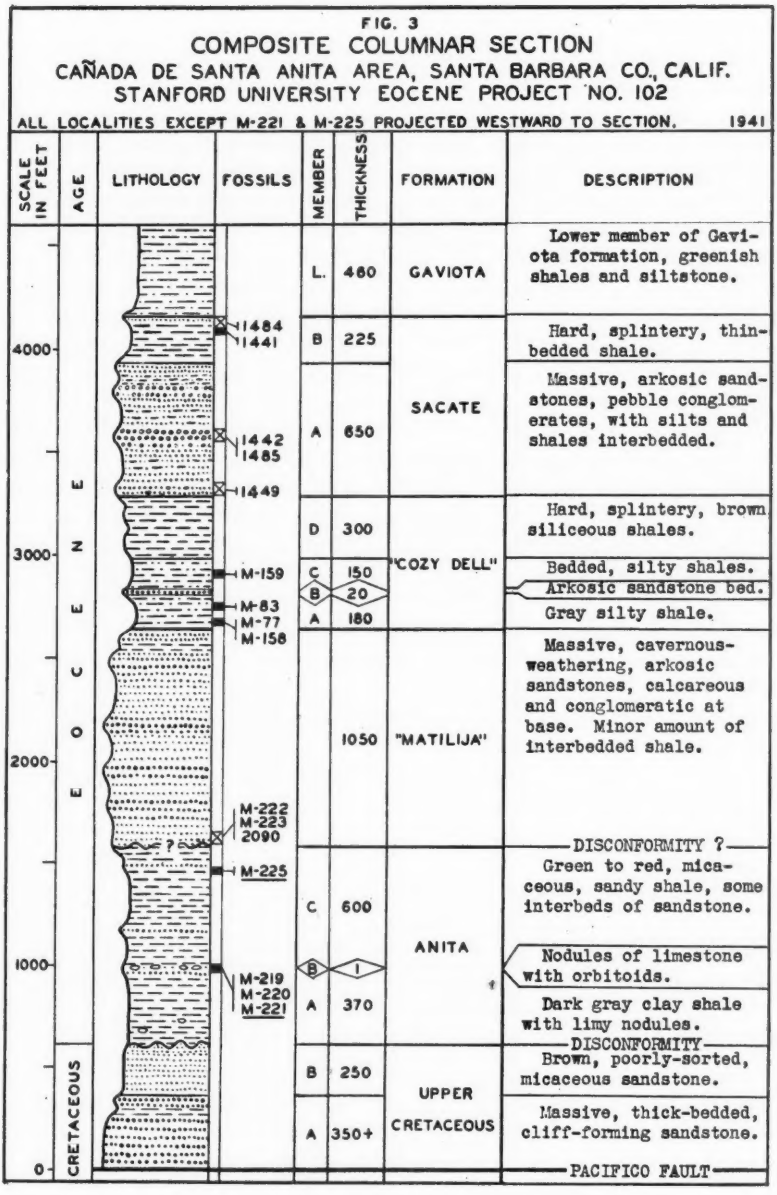

FIG. 3.—Composite columnar section, Cañada de Santa Anita area, Santa Barbara County, California.

FIG. 2.—Geologic map of Cañada de Santa Anita and vicinity, Santa Barbara County, California.

Note on terminology.—The names "Matilija" and "Cozy Dell" were applied by Kerr and Schenck (1928) to divisions of the Eocene rocks of the Ventura region correlative with the type Tejon. The type localities of these formations are more than 55 miles farther east, and though the rocks are in general lithologically and stratigraphically similar, the use of these names is not justified in the area here described until the formations can actually be traced between the two regions, or can be proved exactly correlative by paleontologic means. Many faults and other structural complexities are present in the intervening 55 miles, and much of the country is thickly covered with brush, making it difficult to trace out the units. T. W. Dibblee, Jr.,[3] has mapped the formations in a more or less reconnaissance manner, and believes that the units carry through. These names are used tentatively, then, pending final proof or disproof of their validity.

Similarly, the sandstone between the "Cozy Dell" and the lower Gaviota has been called "Coldwater" (Schenck and Kleinpell, 1936, a), since the evidence indicated it to be the probable equivalent of the Coldwater sandstone of the Ventura region. The name "Coldwater" was first used in California in a casual way by Watts (1896), and gradually came into the literature as a name for a lithogenetic unit. This name is twice preoccupied in American stratigraphy (Wilmarth, 1938, p. 485), and therefore its use as a formational name for these rocks in California is not approved by the United States Geological Survey. For this reason a new local name, Sacate formation, is applied to the sandstones and shales cropping out in the Cañada de Santa Anita area below the Gaviota formation and above the "Cozy Dell" shale.

Upper Cretaceous.—The Upper Cretaceous strata comprise resistant, cliff-forming sandstones with some shale interbeds and, at the top of the sequence, soft, biotitic sandstone. The following is a representative section on the south side of upper Santa Anita Canyon.

		Feet
	Anita shale (Eocene)	
	Disconformity	
Upper Cretaceous	B Poorly sorted, dirty, coarse-grained, brown sandstone; moderately well indurated, grains subangular. Contains an abundance of large flakes of biotite, and here and there some carbonaceous matter. Outcrops poor	250
	A Heavy beds of massive, light gray sandstone; hard, fine- to medium-grained, moderately well sorted, well indurated. Twenty-foot bed of well indurated, gray-green, micaceous shale near top of unit, and other shale interbeds below. Sandstone crops out conspicuously	350+
	Fault contact	

Although fossils are rare in the Cretaceous of the area mapped, they are common at near-by localities. At Locality 1452, in Division "A," occur abundant specimens of a giant *Glycymeris*, *Trigonia*, and other mollusks.

Anita shale.—Lying disconformably above the Upper Cretaceous sandstone is a thick unit of Eocene shales with subordinate beds of sandstone and some limestone nodules (Woodring, 1930, p. 147). At one or more horizons this forma-

[3] Oral communication (1940).

tion includes red foraminiferal shale which has been mentioned by various authors (Reed and Hollister, 1936, p. 90; Dibblee, 1937). The name "Anita shale" is hereby proposed for this unit, which is unnamed in the literature, but has been given various colloquial names by petroleum geologists. The type locality designated is on the south side of Santa Anita Canyon, 1 mile west of Big Bend, where this shale occurs overlying the Cretaceous sandstones and below the "Matilija" sandstone. Localities M-221 and M-225 (Fig. 2) are at the type locality.

Subordinate beds of sandstone and some nodules of limestone occur in the shale. In the lower part is a non-persistent horizon of nodules and lenses of detrital limestone which bear *Discocyclina*. Collections were made from this horizon at Localities M-219, M-220, and M-221, and the species collected are listed in Table I. On the basis of this fauna, this horizon is correlated with the Sierra Blanca limestone of Keenan (1932); it also corresponds in stratigraphic position and lithology, although it was found at only three localities and does not constitute a recognizable continuous cartographic unit.

A section measured at the type locality of the Anita shale is as follows.

		Feet
	"Matilija" sandstone (Eocene)	
	Disconformity	
Anita shale	C Gray-green, micaceous, sandy shale at top, grading down into red, yellow, green or gray shales, in many places micaceous and highly calcareous, with foraminifers abundant at various horizons, especially in the red shales near the top. At various horizons this division contains one or more beds of highly biotitic sandstone, fine to coarse-grained, yellow-brown and poorly indurated. Many of these sandstones are good marker beds over limited areas. Shale outcrops fair	600
	B Non-persistent nodules of brown-weathering, dark gray limestone with *Discocyclina*. At some localities the nodules are composed of hard, medium- to coarse-grained, detrital limestone, with abundant calcareous algae, *Discocyclina*, much glauconite, and ankerite (?) in a sandy matrix	0–1
	A Dark gray, clay shales with greenish gray calcareous and cherty nodules	370
	Disconformity	
	Upper Cretaceous sandstone	

It was not possible to map these divisions as members, due to the scarcity of exposures, but the same succession is recognizable at several localities where the outcrops are good. The age of the Anita shale is tentatively considered to be middle Eocene, on the basis of foraminiferal faunules collected at Localities M-224 and M-225 (Table I). Division "B" is correlative with the Sierra Blanca limestone on the basis of the orbitoid faunules collected at Localities M-219, M-220, and M-221 (see Table I). Keenan (1932, p. 77) concludes that the Sierra Blanca limestone is middle Eocene, stating that it "may have been deposited during either upper Meganos or lower Domengine time."

"Matilija" sandstone.—Concordantly but disconformably overlying the Anita shale is a thick series of heavy, resistant, massive sandstones, to which the name "Matilija" is tentatively applied. The basal bed of the formation is locally conglomeratic, containing a few rounded pebbles in a fine- to medium-grained, sandy matrix, with calcareous cement. This pebbly sandstone in many places contains abundant calcareous algae, which at Locality M-222 make up nearly all of the

TABLE I

CHECK LIST OF ANITA SHALE FOSSILS

	M-219	M-220	M-221	M-224	M-225
Actinocyclina aster Woodring		X			
Amphimorphina ignota Cushman and Siegfus				X	X
Anomalina aragonensis Nuttall				X	X
Anomalina garzaensis Cushman & Siegfus, var.				X	
Asterigerina crassaformis Cushman & Siegfus				X	X
Bulimina cf. *callahani* Galloway & Morrey				X	
Bulimina cf. *declivis* Reuss					X
Bulimina denticulata Cushman & Parker					X
Bulimina excavata Cushman & Parker				X	X
Chilostomella cylindroides Reuss				X	
Cibicides martinezensis Cushman & Barksdale					X
Cibicides cf. *pygmaeus* (Hankten)					X
Clavulinoides cf. *cubensis* Cushman & Bermudez					X
Dentalina communis d'Orbigny					X
Discocyclina psila Woodring	X	X	X		
Dorothia eocenica Cushman				X	
Eponides cocoaensis Cushman				X	
Eponides cf. *tener* H. B. Brady					X
Eponides umbonatus (Reuss) of Cushman					X
Eponides cf. *umbonatus* (Reuss) of Cushman				X	
Fissurina orbignyana Seguenza				X	
Gaudryina coalingensis Cushman & G. D. Hanna				X	
Globigerina bulloides Plummer				X	X
Globorotalia aragonensis Nuttall				X	X
Globorotalia canariensis Galloway & Morrey				X	
Globorotalia cerro-azulensis (Cole)				X	
Globorotalia n. sp. "a" Martin				X	
Globorotalia n. sp. "b" Martin				X	X
Gonatosphaera multicostata (Costa)					X
Gümbelina sp.				X	
Gyroidina obliquata Cushman & McMasters				X	
Lagena conscripta Cushman & Barksdale				X	
Marginulina asperuliformis (Nuttall)				X	X
Marginulina cf. *eximia* Neugeboren of Cushman				X	
Marginulina cf. *laeviuscula* Cushman & Bermudez					X
Nodosarella (?) cf. *constricta* Cushman & Bermudez					X
Nodosaria latejugata Gümbel	X	X		X	
Nodosaria velascoensis Cushman					X
Nonion planatum Cushman & Thomas				X	
Nonion wilcoxensis Cushman & Ponton				X	
Operculina sp.		X			
Plectofrondicularia n. sp. Martin				X	X
Pleurostomella cf. *alternans* Schwager				X	
Pleurostomella nuttalli Cushman & Siegfus					X
Pseudoglandulina laevigata (d'Orbigny)					X
Pullenia eocenica Cushman & Siegfus				X	
Pulvinulinella tenuicarinata Cushman & Siegfus				X	X
Robulus large sp.	X	X			
Textularia mississippiensis Cushman of Cushman & Hanna				X	
Tritaxilina colei Cushman & Siegfus				X	X
Tritaxilina pupa (Gümbel) of Cushman				X	X
Calcareous algae	X	X	X		
Echini spines and plates	X	X			
Mollusk fragments	X	X			
Ostracodes	X				
(Glauconite)	X	X	X		

rock. This horizon is the algal sandstone above the red shale as reported by Gill (1937) near Las Cruces. At other localities this basal sandstone contains many shell fragments, and at one place (Loc. 2,090) a molluscan faunule was collected. This basal facies of the "Matilija" is neither glauconitic nor micaceous.

The main part of the "Matilija" is composed of massive beds of cavernous-

TABLE II

CHECK LIST OF "MATILIJA" FOSSILS

	2090	*M-222*	*M-223*
Pelecypoda			
Gari hornii (Gabb)	X		
Macrocallista hornii (Gabb)	X		
Microcallista tecolotensis (M. A. Hanna)	X		
Nemocardium linteum (Conrad)	X		
Pholadomya sp.	X		
Pitar uvasanus (Conrad)	X		
Schedocardia cf. *brewerii* (Gabb)	X		
Gastropoda			
Amaurellina aff. *cortezia* Gardner & Bowles	X		
Amaurellina aff. *moragai* Stewart	X		
Ectinochilus canalifer supraplicatus (Gabb)	X		
Ficopsis hornii (Gabb)	X		
Ficus mamillata (Gabb)	X		
Galeodea susanae Schenck	X		
"*Murex*" (?) *whitneyi* (Gabb)	X		
Olequahia cf. *hornii* (Gabb)	X		
Seraphs erratica (Cooper)	X		
Surculites sinuatus (Gabb)	X		
Turritella scrippsensis M. A. Hanna	X		
Voluta martini Dickerson	X		
Bryozoa	X		
Calcareous algae	X	X	X

Note: No glauconite is associated with the calcareous algae in the basal "Matilija."

weathering sandstone ranging up to 50 feet in thickness. It is a fine- to coarse-grained, dirty, arkosic sandstone, light gray, weathering to yellow-brown, with abundant large flakes of biotite reaching 2 mm. in size, and is poorly cemented and markedly porous. Between the uppermost sandstone beds and the main mass of the "Matilija" is a shale break of greenish gray, micaceous, silty, slightly calcareous shale. Outcrops of this shale are rare. Due to the brush cover, it was impractical to map separate members in the "Matilija." The thickness of the formation is about 1,050 feet.

On the basis of megafossils listed in Table II, the "Matilija" is correlated with the "Transition stage" of Clark and Vokes (1936), and the Liveoak member of the type Tejon formation as defined by Marks (1941). Gill's (1937) suggestion of contemporaneity with the Sierra Blanca limestone on the basis of nullipores does not hold, as the equivalent of the Sierra Blanca limestone occurs in the Anita shale below this algal sandstone.

The occurrence of *Turritella scrippsensis* (M. A. Hanna) in this formation is

worthy of special note; and in order that a permanent record may be made of the specimen, it is illustrated on the accompanying Plate I, Figure 10. Also shown on this plate are figures of other specimens of *Turritella* which are of special importance in correlations.

"Cozy Dell" shale.—Conformably overlying the "Matilija" is a unit of argillaceous and siliceous shales with subordinate sandstone, provisionally called the "Cozy Dell" shale. Four members were differentiated and carried in the mapping. Two strike faults are shown on the map, and both of these run for part of their course in the "Cozy Dell," repeating various parts of it (see cross section, Fig. 4). In some places beds are repeated twice and, as some of these shales crop out poorly, it was essential to map in as detailed a manner as possible to establish the undisturbed stratigraphic section and decipher the faulting.

The following section was measured ½ mile south of upper Santa Anita Canyon.

		Feet
	Sacate sandstone	
	Conformity	
"Cozy Dell" shale	D Splintery, thin-bedded, chocolate-brown, siliceous shales, clean, hard; here and there fine-grained sandier beds an inch or so thick. In eastern part of area a horizon of concretionary, yellow-weathering, gray limestone nodules up to 2 feet in diameter occurs near top of member within a few feet of Sacate contact. Shale is distinctly harder at two horizons, so that outcrops of this member have a double aspect. These siliceous shales commonly support scattered growth of small oaks. Outcrops fairly good	300
	C Gray, yellow-brown, or light chocolate-brown shales closely but indistinctly bedded; siltier than member "D" and with poorer outcrops. In places foraminiferal, with "*Planularia*" *markleyana* fauna of Church (1931) at Loc. M-159	150
	B Persistent bed of fine- to coarse-grained, arkosic sandstone, yellow-gray, dirty, micaceous, with unweathered biotite flakes to 2 mm. in size. In places calcareous, high content of ferro-magnesian minerals. In some places hard, platy-weathering, well washed conglomeratic sandstones, with shale and other pebbles and carbonized wood appear at various horizons in lower part of "Cozy Dell." Outcrops good	5–20
	A Hard to soft, gray, silty or sandy shale, poorly sorted, in places micaceous and calcareous becoming harder and with less silt above. At some horizons foraminifers are abundant, and faunules were collected at Locs. M-77, M-83, and M-158. Outcrops poor	180
	Conformity	
	"Matilija" sandstone	

On the basis of foraminifers recorded on the accompanying check list (Table III), member "A" of the "Cozy Dell" is correlated with Laiming's Zone A-2, and the faunule from member "C" (Loc. M-159) may be between Zones A-2 and A-1. No faunal control is available on member "D."

Sacate formation.—Conformably above the siliceous shales at the top of the "Cozy Dell" is a succession of sandstones and interbedded silty and shaly strata. For the reasons mentioned, the name Sacate formation is hereby proposed for this cartographic unit, with the type locality designated as Sacate Canyon. The formation comprises the beds of sandstone and shale occurring there above the siliceous shales of member "D" of the "Cozy Dell," and below the lower siltstone member of the Gaviota formation. Localities 1,449, 1,485, and 1,484 (Fig. 2) are at the type locality.

Considerable lateral variation makes it impractical to delimit more than two

members of this formation. In Sacate Canyon three well defined massive sandstones crop out and are separated by sandy shales. These sandstones, however, lose their identity toward the east and west. Conglomerate lenses appear at

TABLE III

CHECK LIST OF "COZY DELL" FORAMINIFERA

	M-77	*M-83*	*M-158*	*M-159*
Asterigerina crassaformis Cushman & Siegfus				X
Bathysiphon eocenica Cushman & G. D. Hanna			X	
Bolivina capdevilensis Cushman & Bermudez				X
Bulimina adamsi Cushman & Parker	X			
Bulimina capitata Yokoyama of Cushman & Dusenbury	X			
Bulimina lirata Cushman & Parker	X			
Bulimina microcostata Cushman & Parker		X		
Cassidulina globosa Hankten	X			X
Cibicides cushmani Nuttall		X		X
Cibicides cf. *westi* Howe	X			
Dorothia cf. *eocenica* Cushman	X			
Eponides cocoaensis Cushman		X		
Eponides pygmaeus Hankten	X	X		X
Eponides minimus Cushman		X		X
Eponides tener H. B. Brady				X
Eponides umbonatus (Reuss)	X			
Globigerina bulloides d'Orbigny	X			X
Globigerina triloculinoides Plummer				X
Globigerina cretacea d'Orbigny	X			
Globorotalia n. sp. "b" Martin				X
Gümbelina cf. *striata* (Ehrenberg) of Cushman & Dusenbury				X
Gyroidina obliquata Cushman & McMasters		X		
Gyroidina octocamerata Cushman & G. D. Hanna	X			
Gyroidina cf. *subangulata* (Plummer)	X			
Haplophragmoides emaciatum (Brady)				X
Marginulina subbulata Hankten of Nuttall				X
Nodosaria arundinea Schwager of Cushman & Hanna				X
Nodosaria consobrina d'Orbigny of Cushman & Hanna	X			
Nodosaria ewaldi Reuss			X	
Nodosaria cf. *pyrula* d'Orbigny of Howe				X
Nonion planatum Cushman & Thomas				X
"Planularia" markleyana Church				X
Plectina dalmatina Liebus of Nuttall				X
Plectofrondicularia aff. *packardi* Cushman & Schenck	X			
Plectofrondicularia sp.		X		X
Pseudoglandulina laevigata (d'Orbigny)				X
Pullenia cf. *quinqueloba* (Reuss)				X
Pulvinulinella tenuicarinata Cushman & Siegfus				X
Robulus inornatus (d'Orbigny)	X			
Robulus welchi Church	X	X		X
Textularia agglutinans d'Orbigny of Nuttall				X
Textularia mississippiensis Cushman of Cushman & Hanna				X
Uvigerina garzaensis Cushman & Siegfus	X			X
Virgulina cf. *bramletti* Galloway & Morrey				X

several horizons, and some of them contain fossils. The upper member is a distinctive siliceous shale with some lenses of sandstone.

The generalized, composite sequence is as follows, with thickness taken from the type section in Sacate Canyon.

		Feet
	Lower Gaviota (type)—siltstone with Refugian fossils	
	Conformity	
Sacate formation	B Splintery, brown shales, hard, thin-bedded and well washed. Contains here and there non-persistent sandstone beds and, on ridge east of Sacate Canyon, a limestone conglomerate with *Turritella*, sp. "A" (Pl. 1, Figs. 9, 12, 14), (Loc. 1,484). This shale member is comparatively thin, remarkably persistent, and an excellent marker bed. Mapping is aided by scattered growth of small oaks that this shale supports. Outcrops good	170
	A Alternating beds of sandstone, shale, and some conglomerate. Basal sandstones massive, hard, fine- to medium-grained; light gray, yellowish, or brown; contain much biotite. This sandstone weathers in flagstone-like slabs The basal sandstone becomes conglomeratic and fossiliferous at various localities along strike, e.g., Loc. 1,449. Lenses of conglomerate are present higher in section and reach best development between Agua and Santa Anita canyons where heavy conglomerate contains well rounded, flattish pebbles reaching 2 inches or more in size. Conglomerate contains fragments of oyster shells and is very well cemented, fracturing across quartz pebbles The sandstone beds are separated by siltstone and brown, micaceous shale which is in many places somewhat siliceous. Sandstones crop out well, but silts and shales are generally obscured by brush	880
	Conformity	
	"Cozy Dell" shale	

Plate I

Fig. 1.—*Turritella variata* Conrad cf. var. *juliana* Merriam, U.C. Hypotype 33911; Loc. A-948, north side of Santa Ynez Mountains. Gaviota formation. Length of specimen, 36 mm.; width, 20 mm.

Fig. 2.—*T. applinae* Hanna, Stanford Univ. Paleo. Type Coll. No. 7413, L.S.J.U. Loc. 2,105, Santa Anita Canyon area, western Santa Ynez Mountains. "Matilija" sandstone (Eocene). Length of specimen, 19 mm.; width, 10 mm.

Fig. 3.—*T. variata* Conrad, U.C. Hypotype 33905; Loc. A-948, same as for Fig. 1. Length of specimen, 70 mm.; width, 21 mm.

Fig. 4.—*T. lorenzana* Wagner and Schilling; holotype, U.C. Mus. Pal. No. 11424; Loc. 3,217, Kern Co., California. Holotype said by Wagner and Schilling to have come from the Pleito; but Merriam thinks this may be an error, as the species seems to be confined to the San Emigdio formation. Length of specimen, 34 mm.; width, 15 mm.

Fig. 5.—*T. variata* Conrad, of Clark and Anderson, U.C. Hypotype 11058; Dry Creek, 6 miles northeast of Wheatland, Yuba Co., Calif. Wheatland formation (type), Eocene. Length of specimen, 59 mm.; width, 20 mm.

Fig. 6.—*Turritella* sp. "B," Stanford Univ. Paleo. Type Coll. No. 7238, L.S.J.U. Loc. 2,379, Kennedy Canyon near Matilija Springs, Ventura Co., Calif. "Coldwater" sandstone. Length of specimen, 36 mm.; width, 12 mm.

Fig. 7.—*T. variata* Conrad, U.C. Type No. 33906; Loc. A-948, same as for Fig. 1. Length of specimen, 33 mm.; width, 16 mm.

Fig. 8.—*T. variata* Conrad, of Clark and Anderson, U.C. Hypotype 11024; Wheatland formation, Loc. same as Fig. 5. Length of specimen, 46 mm.; width, 14 mm. Compare this figure with those of topotypes of *variata*, Figs. 3 and 7.

Fig. 9.—*Turritella* sp. "A," Stanford Univ. Paleo. Type Coll. No. 7414, L.S.J.U. Loc. 1,484, Santa Anita Canyon area, western Santa Ynez Mountains. Sacate formation (Eocene). Length of specimen, 50 mm.; width, 19 mm.

Fig. 10.—*T. scrippsensis* Hanna, Stanford Univ. Paleo. Type Coll. No. 7415; Loc. 2,090, Santa Anita Canyon area, western Santa Ynez Mountains. "Matilija" sandstone (Eocene). Length of specimen, 32 mm.; width, 16 mm.

Fig. 11.—*T. wheatlandensis* Clark and Anderson, Holotype, U.C. Mus. Pal. No. 11059; Wheatland formation, Loc. same as Fig. 5. Length of specimen, 53 mm.; width, 23 mm. Compared with the specimen shown in Fig. 14 this species differs in whorl profile and number of spiral ribs.

Fig. 12.—*Turritella* sp. "A," Stanford Univ. Paleo. Type Coll. No. 7414, L.S.J.U. Loc. 1,484. Same specimen as Fig. 9, but enlarged to show details of sculpture. Width, 19 mm.

Fig. 13.—*T. variata* Conrad of Clark and Anderson, U.C. Hypotype 11012; Wheatland formation. Loc. same as for Fig. 5. Length of specimen, 38 mm.; width, 11 mm.

Fig. 14.—*Turritella* sp. "A," Stanford Univ. Paleo. Type Coll. No. 7414, L.S.J.U. Loc. 1,484. Same specimen as shown in Figs. 9 and 12, but enlarged to show detail of sculpture. Width, 19 mm.

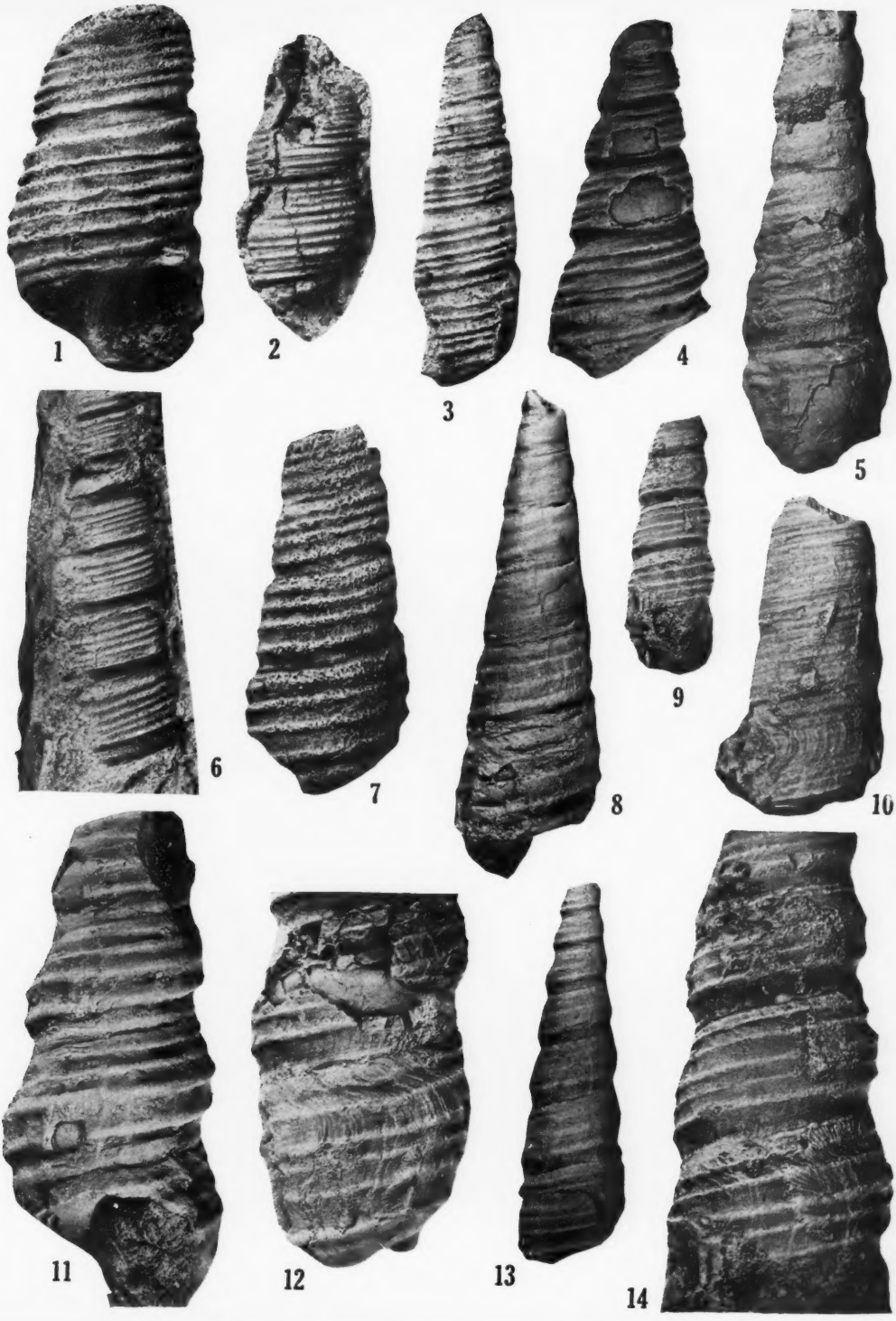

PLATE I.—Significant specimens of *Turritella* from the Eocene of California.

Well preserved megafossils are rare in member "A" of the Sacate. The best ones are from Locality 1,442; they are *Ostrea idriaensis* Gabb; *Venericardia* cf. *hornii* (Gabb); *Cypraea* sp.; "*Natica*" *uvasana* Gabb; and *Turritella* sp. "A." Less abundant mollusks are present at Localities 1,449 and 1,485. Arenaceous *Foraminifera* are present in member "B" at Locality 1,441. At the top of this member (Loc. 1,484), the specimen of *Turritella* sp. "A" (Pl. I, Figs. 9, 12, and 14) was collected. Locality 1,484 is just below the basal Gaviota in a bed of sandstone and limestone-conglomerate.

The occurrence of this *Turritella* at Locality 1,484 is worthy of special note. In spite of careful comparison with much material, no specific name can be assigned to it at present. It has some similarity to the type of *T. variata* Conrad (as figured by Schenck and Keen, 1940, Pl. 14, Fig. 7), *T. lorenzana*, *T. lompocensis*, "*T. variata*" from the Wheatland (Clark and Anderson, 1938), and *T. wheatlandensis*, but the Sacate specimen is identical with none of these. Comparison with several topotypes of *T. variata* show it to be similar, but not identical. Clark (Clark and Anderson, 1938) placed *T. lompocensis* and *T. lorenzana* in synonymy with *T. variata*, but Merriam (1941) does not agree with this interpretation. All of these forms appear to be closely related, and the Sacate specimen belongs in this group.

Comparison of the Sacate specimen with *Turritella* sp. "B" (Pl. I, Fig. 6) from the "Coldwater" sandstone near the Ventura River shows the two to be different. Further, comparison of *Turritella* sp. "A" with material collected by T. W. Dibblee, Jr., from 300 feet below the top of the "Coldwater" sandstone on the old San Marcos Grade shows that the two are different species.

On the basis of *Turritella* sp. "A," it appears that the Sacate formation may be correlated, at least in part, with the Wheatland formation of Clark and Anderson (1938). The dissimilarity of "Coldwater" and Sacate *Turritellas* may be indicative of difference in age; but on the basis of superposition, some part of the Sacate may be equivalent to some part of the loosely defined "Coldwater" formation of the Ventura Basin. Because faunules from member "A" of the "Cozy Dell" fall in Laiming's Zone A-2, and the faunule from member "C" of the "Cozy Dell" (M-159) belongs between A-2 and A-1, at least some part of the Sacate must fall in Laiming's A-1. This places the Sacate as a correlative of part of the Kreyenhagen shale of the San Joaquin Valley. Furthermore, on the basis of foraminifers, the Sacate is correlative with part of the "Kreyenhagen" of Taff (1935) on the north side of Mount Diablo.

GEOLOGIC STRUCTURE

Traveling northward from the ocean at the mouth of Gaviotita Canyon along U. S. Highway 101, one passes first through up-ended Modelo and Rincon shales (Miocene); then the hills rise more abruptly as the road cuts through the steeply dipping, brush-covered sandstones of the Vaqueros and Sespe formations. The Gaviota formation forms the narrow pass itself, and another 970 yards up the

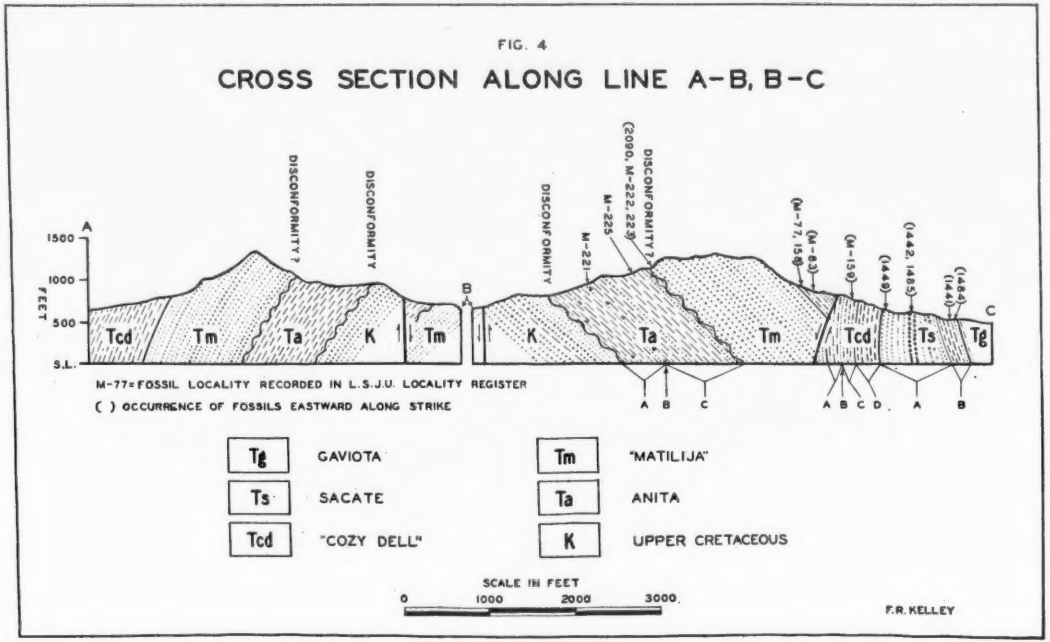

FIG. 4.—Cross section along lines *AB*, *BC*, shown on geologic map, Figure 2.

road the Vaqueros is again present with the strata still dipping toward the south. Farther north, the descending section is repeated until the top of the grade is reached, and here the Modelo shales crop out again. Continuing northward toward Buellton, the sequence is repeated for the third time in the same descending order. These three blocks are separated by branches of the Santa Ynez fault, and these branches determine the structural pattern of the region. This structural setting is clearly shown on the generalized tectonic map of southern California compiled by Reed and Hollister (1936, Pl. 1). The map shows the Santa Ynez fault crossing the smaller area reported upon in this paper (Fig. 2). That this is not a simple fault but a complex fault zone is well known.

The most continuous and unbroken stratigraphic section shown on the map in Figure 2 is between Cañada de Santa Anita and Arroyo El Bulito; here the structure is homoclinal, with all the formations from the Cretaceous to the Modelo shale superposed in normal sequence. The Santa Ynez fault has its downthrown side on the north, and in this area are two minor faults of the same nature—causing repetition of strata, again with the downthrown side on the north. These small faults repeat several beds or members, however, instead of several formations. They are in most places vertical, but in other places dip at a high angle toward the north.

Above Big Bend in Santa Anita Canyon, the strata on the south side are matched by their counterparts on the north. These dip northward to form the north limb of a broad anticlinal structure plunging to the east. This anticline, however, has been modified by faulting and overturning, and the center of the arch, represented by the valley of Santa Anita Creek, has dropped down in a graben-like block between two faults which converge toward the west. This block itself is made up of two elements separated by the extension of the northern branch of the Santa Ynez fault. The strata in the southern part of the block dip normally south in upper Sacate Canyon in accordance with the general homoclinal structure. Then they gradually steepen to vertical at Big Bend and overturn farther west until they attain an overturned dip of 45° N. The strata of the northern part of the block dip gently south in normal stratigraphic sequence.

North of the down-dropped central block, the dip of the formations is generally northward, but is interrupted just west of Gaviotita Canyon by a peculiar type of overturning between two "tear faults." The strata are dipping normally on the two sides of the small disturbed area, but between the two faults they are overturned. Gaviotita Canyon follows the eastern fault; here opposite dips are recorded in the "Matilija" on the two canyon sides, but at the mouth of the canyon no offset is present in the "Matilija"-"Cozy Dell" contact. At this point the beds on the two sides steepen within a short distance to vertical and cross the creek unbroken. Therefore this faulting is superficial, as it has affected only the upper parts of the outcrops. The fault bounding the overturned area on the west has had greater movement, as the Anita-"Matilija" contact is considerably offset.

The accompanying cross sections (Fig. 4) illustrate the general domal structure of the formations near the head of Cañada de Santa Anita. The "Matilija" is approximately the same thickness on the two limbs of the faulted anticline. The Anita shale, however, is 260 feet thinner on the north than on the south flank.

The cross section (*BC*) from the Pacifico fault southeasterly to the divide between the east and west forks of Agua Creek shows the steeply inclined strike fault in the "Cozy Dell" shale. The observer will note that the shale is overturned on the south side of the fault and that the beds in a short distance assume their normal south dips. Marked overturning also occurs in the "Matilija" and younger formations west of Agua Canyon (Fig. 2), and local overturning may be seen in the headwater area of Sacate Canyon. Local flexures in the shales are especially well exposed in Sacate Creek.

REGISTER OF LOCALITIES

All localities are in the southern part of the Lompoc Quadrangle, Santa Barbara County, California. The numbers refer to Stanford University locality registers.

MEGAFOSSIL LOCALITIES

1,442

Cañada de Santa Anita, 10-foot interbedded conglomerate and sandstone on east bank of creek just above trail due west of northern edge of first "a" in "Santa."
Formation: Sacate (Eocene), about 650 feet below top.
Faunule: Mollusks.
Collectors: R. M. Kleinpell, H. G. Schenck, and H. D. Hedberg, 1934.

1,449

Elevation 600± feet, west fork of Sacate Canyon on east side of creek in prominent sandstone in Sacate (Eocene) formation.
Collectors: R. M. Kleinpell, K. Krauskopf, and H. G. Schenck, July 31, 1935.
(*Note:*—Sacate Canyon is mislabelled on the Lompoc Quadrangle; actually, the unlabelled canyon 2,000 feet east should be labelled Sacate Canyon, and the one bearing this name at present should be changed to Coyote Canyon on the U.S.G.S. map.)

1,452

Elevation 1,250± feet, 0.07 inch north of 34° 30′ latitude line, 0.4 inch west of 120° 20′ longitude line; Cañada de Santa Anita drainage, first ridge south of main creek, about one mile N. 78° E. of hill 1,715, and about ¼ mile southeast of conspicuous rock in creek bottom.
Formation: "Chico" sandstone, Cretaceous.
Collectors: T. W. Dibblee, Jr., 1931; K. Krauskopf and H. G. Schenck, Aug. 1, 1935.

1,484

On spur at head of west fork of Quarta Canyon about 1⅛ miles north of ocean, on 900-foot contour.
Formation: Uppermost thin sand bed of member "B," Sacate formation (Eocene), and just below basal Gaviota silt.
Faunule: Turritella, sp. "A"
Collector: T. W. Dibblee, Jr., 1937.

1,485

Same canyon as Locality 1,449, 500 feet downstream.
Formation: Member "A" of Sacate (Eocene); same horizon as Locality 1,442.
Faunule: Mollusks.
Collectors: R. M. Kleinpell and H. G. Schenck, 1935.
(Fossils occur in thin conglomerate bed in sandstone.)

2,090

Santa Anita drainage, elevation 1,100± feet, about 3,000 feet N. 35° W. from creek intersection at Big Bend of Cañada de Santa Anita.

Formation: "Matilija" sandstone (Eocene).

Faunule: Ficopsis, Turritella, et cetera.

Collectors: T. W. Dibblee, Jr., H. W. Hoots, M. Payne, H. G. Schenck, and R. White, Aug. 7, 1936; T. W. Dibblee, Jr., and F. R. Kelley, 1939; Harold B. Foxhall, 1941.

MICROFOSSIL LOCALITIES

1,441

Cañada de Santa Anita, west bank of creek, S. 45° W. of southwesterly tip of first "a" in "Santa." Outcrop consists of about 100 feet of rusty- and gray-weathering, purplish, dark brown and gray, finely splintery, moderately tough clay shale.

Formation: Sacate (Eocene), within upper 125 feet (member "B").

Faunule: Foraminifera.

Collectors: R. M. Kleinpell, H. G. Schenck, and H. D. Hedberg, 1934.

Divisions of Locality: (a) From 10 to 12 feet stratigraphically above base of shale exposure (Santa Anita #83-A); (b) about 25 feet above base of exposure (Santa Anita #83-B); (c) about 30 feet above base (Santa Anita #3); (d) about 40 feet above base (Santa Anita #83-C); (e) about 50 feet above base (Santa Anita #2); (f) from 55 to 60 feet above base (Santa Anita #83-D).

M-77

Sacate drainage, 5,625 feet N. 67° E. of Big Bend in Cañada de Santa Anita, and 2,870 feet S. 82° W. of top of Hill, 1,480. Headwaters of east fork of Sacate Creek on north side of small gully following "Matilija"-"Cozy Dell" contact.

Formation: "Cozy Dell" (Eocene), member "A," in silty gray shales near base of formation about 20 feet stratigraphically above contact with underlying sandstone.

Fauna: Bulimina corrugata, et cetera.

Collector: F. R. Kelley, February, 1940.

M-83

Sacate drainage, 2,850 feet due east of Big Bend in Cañada de Santa Anita. Near headwaters of west fork of Sacate Creek above upper repetition of "Matilija," near old cabin, about 60–80 feet northwest of two eucalyptus trees below cabin, in bottom of small tributary gully coming in from east side of canyon.

Formation: "Cozy Dell" (Eocene), member "A," in silty gray shale with sandstone interbeds.

M-83a—about 100 feet downstream from M-83, 40 feet southwest of same tree in east creek bank of main stream.

Collector: F. R. Kelley, Feb. 20, 1940.

M-158

Santa Anita drainage, 1,120 feet S. 12° E. of Big Bend and about 1,200 feet downstream in bottom of Cañada de Santa Anita.

Formation: "Cozy Dell" (Eocene), member "A," about 10 feet stratigraphically above topmost foot-thick beds of sandstone in main "Matilija." Massive gray shale outcrop on west side of creek about 10 feet above water level.

Collector: F. R. Kelley, March 1, 1940.

M-159

Sacate drainage, 4,500 feet S. 83° E. of Big Bend in Cañada de Santa Anita; bottom of canyon, east fork, Sacate Canyon, 2,150 feet upstream from junction with west fork.

Formation: "Cozy Dell" (Eocene), member "C," in sliding slope of shale, facing southwest on west side of creek, stream bank opposite little flat north of "Cozy Dell"—Sacate contact.

Collector: F. R. Kelley, March, 1940.

M-219

Santa Anita drainage, 1,620 feet N. 14° W. of Big Bend in Cañada de Santa Anita; on southwest-facing ridge between two gullies. Grassy hillside, fossils from large limestone nodules in the soil (no outcrop).

Formation: Anita shale (Eocene), member "B."

Collector: F. R. Kelley, Feb. 18, 1940.

M-220

Santa Anita drainage, 2,230 feet N. 55° W. of Big Bend in Cañada de Santa Anita; in tributary gully running south directly into main Santa Anita Creek. In overturned area, about 10 feet strati-

graphically below highest conspicuous sandstone bed. No outcrop; fossils from two weathered nodules of limestone in poor outcrop of red foraminiferal shale.
Formation: Anita shale (Eocene), member "B."
Collector: F. R. Kelley, Feb. 21, 1940.

M-221

Santa Anita drainage, 5,170 feet S. 87° W. of Big Bend in Cañada de Santa Anita; on south side of canyon in "Waterfall Creek" above falls. East fork of this creek, west side, one-quarter of distance from prominent 3-foot sandstone bed outcrop to San Julian Ranch fence. Limestone nodule on grassy hillside.
Formation: Anita shale (Eocene), member "B," equivalent of Sierra Blanca limestone.
Collector: F. R. Kelley, April 16, 1940.
(This locality is in type locality of Anita shale.)

M-222

Santa Anita drainage, 3,110 feet N. 22° W. of Big Bend in Cañada de Santa Anita; on northwest-facing slope below top of ridge followed by old road grade.
Formation: "Matilija" sandstone (Eocene), basal beds above red shale.
Collectors: W. A. Newton and F. R. Kelley, 1939.

M-223

Santa Anita drainage, 1,200 feet N. 8° W. of Big Bend in Cañada de Santa Anita; in vertical beds of algal conglomeratic sandstone at top of hill immediately north of Big Bend.
Formation: "Matilija" sandstone (Eocene), basal beds.
Collector: F. R. Kelley, Feb. 18, 1940.

M-224

Santa Anita drainage, 2,000 feet N. 6° W. of Big Bend in Cañada de Santa Anita; below top of divide in head of tributary creek flowing southwest into Santa Anita.
Formation: Anita shale (Eocene), member "A."
Collector: F. R. Kelley, February, 1940.

M-225

Santa Anita drainage, 5,880 feet S. 82° W. of Big Bend in Cañada de Santa Anita; in upper part of "Waterfall Creek" above the falls, in head-gullied part of one of the tributaries.
Formation: Anita shale (Eocene), member "C."
Collector: F. R. Kelley, April 29, 1940.

LOCALITIES OF FOSSILS ILLUSTRATED ON PLATE I

University of California Locality 3,217

California, Kern County, Mt. Pinos Quadrangle. East center, SW. ¼ Sec. 21, T. 10 N., R. 21 W., near base of bluffs on east side of Pleitito Creek and ¾ mile north of Rock Springs. Pleito formation. (From Wagner and Schilling, 1923, p. 263; see also Merriam, 1941, p. 100)

University of California Locality A-948

California, Santa Barbara County, Lompoc Quadrangle; 300 feet north of Locality A-947. Locality A-947 is described as follows by collector (Wm. Effinger): "500 feet east of highway bridge, Nojoqui Creek, about 1.2 miles north of Gaviota Pass; shales with red stringers directly overlying coarse sandstone beds containing *Turritella variata*."

University of California Wheatland Locality

California, Yuba County, Smartsville Quadrangle (1/125,000). Type locality of Wheatland formation; 6 miles northeast of Wheatland at east margin of Sacramento Valley. Outcrops on east side of Dry Slough, or Dry Creek, as it is called on the later Spenceville Quadrangle (1/31,680), about 300 feet east of southwest corner of NW. ¼, SW. ¼ Sec. 7, T. 14 N., R. 6 E. (projected into Johnson Rancho).
Fossils occur in most northerly exposure along Dry Creek, in pebble-cobble conglomerate, resting on channeled, massive, tuffaceous sandstone.
(Same locality as L.S.J.U. Locality 2,367).

Stanford University Locality 2,105

California, Santa Barbara County, Lompoc Quadrangle. El Jaro Creek drainage, 4,300 feet N. 27° E. from Big Bend in Cañada de Santa Anita.
Formation: Conglomerate in "Matilija" sandstone (Eocene).

Stanford University Locality 2,379

California, Ventura County, Ventura Quadrangle. One mile southeast of Matilija, part way up

south wall of Kennedy Canyon on 1,150-foot contour, near end of prominent ridge bordering Kennedy Canyon on south, 1,400 feet due west of Ventura River.

Formation: Lower "Coldwater," about 550 feet stratigraphically above Cozy Dell contact.

Stanford University Localities 1,484 and 2,090

Descriptions are given on a previous page.

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VOL. 27, NO. 1 (JANUARY, 1943), PP. 20-37, 13 FIGS.

BOWERS FIELD, MONTAGUE COUNTY, TEXAS[1]

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ABSTRACT

The Bowers field was discovered in April, 1939, and had produced approximately 480,000 barrels of oil to April 1, 1942. Cretaceous, Pennsylvanian, and probable pre-Cambrian are represented in part. Oil is produced from eight separate formations of Pennsylvanian age. It is felt that stratigraphic variation is the predominant factor in controlling accumulation in the greater part of these zones. Structure increases materially with depth and is thought to be the result of differential compaction over a buried granite ridge. Geologic history includes several periods of long-continued erosion, and at least one probable period of minor unconformity.

INTRODUCTION

Relatively complete data are available on the Bowers field. Of the 45 wells drilled in and around the field since its discovery, electric logs have been run on 34 which, when supplemented by microscopic lithologic work, are extremely reliable. The writer has been directly concerned with geologic investigation in the Bowers area for the past 2 years.

ACKNOWLEDGMENTS

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LOCATION

The Bowers field is located approximately 5 miles north of the town of St. Jo and 4 miles northeast of Bonita in the northeastern part of Montague County, Texas (Fig. 1). The area is traversed by several gravel and native soil farm-to-market roads. The field is serviced by but one pipe line.

PRODUCING HISTORY

The history of the Bowers field is one of sporadic development, each period of activity being set off by the discovery of a new producing formation. In April, 1939, Benton and Holmes completed their Joe Bowers No. 1 (Fig. 2) as the discovery well at a total depth of 2,958 feet producing initially 76 barrels per day on the pump after shot. This discovery was followed by another completion in the "Bowers sand" (Fig. 3), United Producers' and Continental's Langford No. 1 drilled as a south offset.

In July, 1939, Benton and Holmes brought in their Joe Bowers No. 2 (Fig. 2) as the discovery well in the "granite wash" (Fig. 3). This well flowed 69½ bar-

[1] Manuscript received, June 18, 1942.

[2] Chief geologist, the Mudge Oil Company.

rels in 3 hours through open 2-inch tubing, with total depth at 3,869 feet and casing set at 3,826 feet. Its east offset, the Phillips Petroleum Company's Custers No. 1, proved dry in the "granite wash" and was plugged back to 2,895 feet. In November, 1939, after being shot at 2,882 feet to 2,890 feet, it was completed pumping 15 barrels of oil in 24 hours fron an erratic sand just above the "Bowers sand." This zone is probably equivalent to the sand which later produced in the

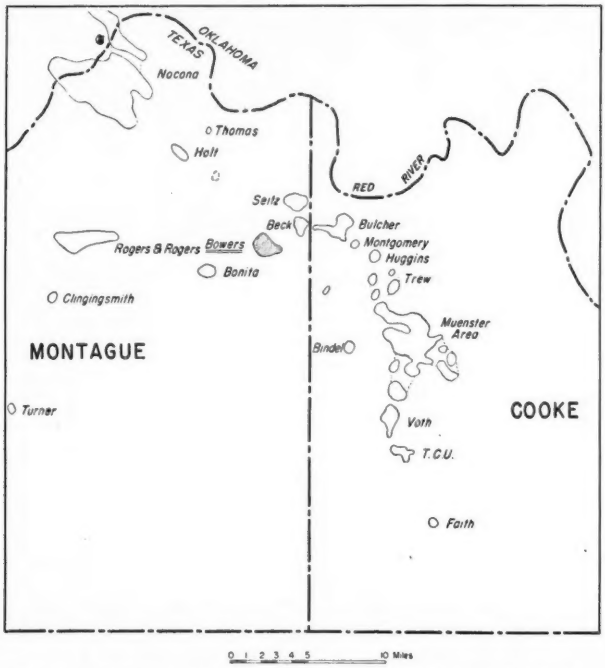

FIG. 1.—Index map showing location of Bowers field (cross-hatched).

Pace Petroleum Company, Inc., M. M. Gilbert No. 1, and which, for the purposes of this paper, has been called the "Gilbert sand" (Fig. 3).

Somewhat later, the United Producers and Continental deepened an old abandoned hole on the Rich land (Fig. 2) east of the then established production. The "Bowers sand" was not present and the "granite wash" reportedly yielded only minor showings, but pipe was set and perforations made in three possible zones as shown by electric log. These perforations, at 2,994–3,002 feet, 3,030–3,046 feet, and 3,451–3,495 feet, resulted in production from one, and possibly more, of these zones. With the setting of a tubing packer, the major part, if not all, of the production was determined to be coming from the perforations at 3,451–3,495 feet. Thus, in December, 1939, a fourth producing zone, the "Rich

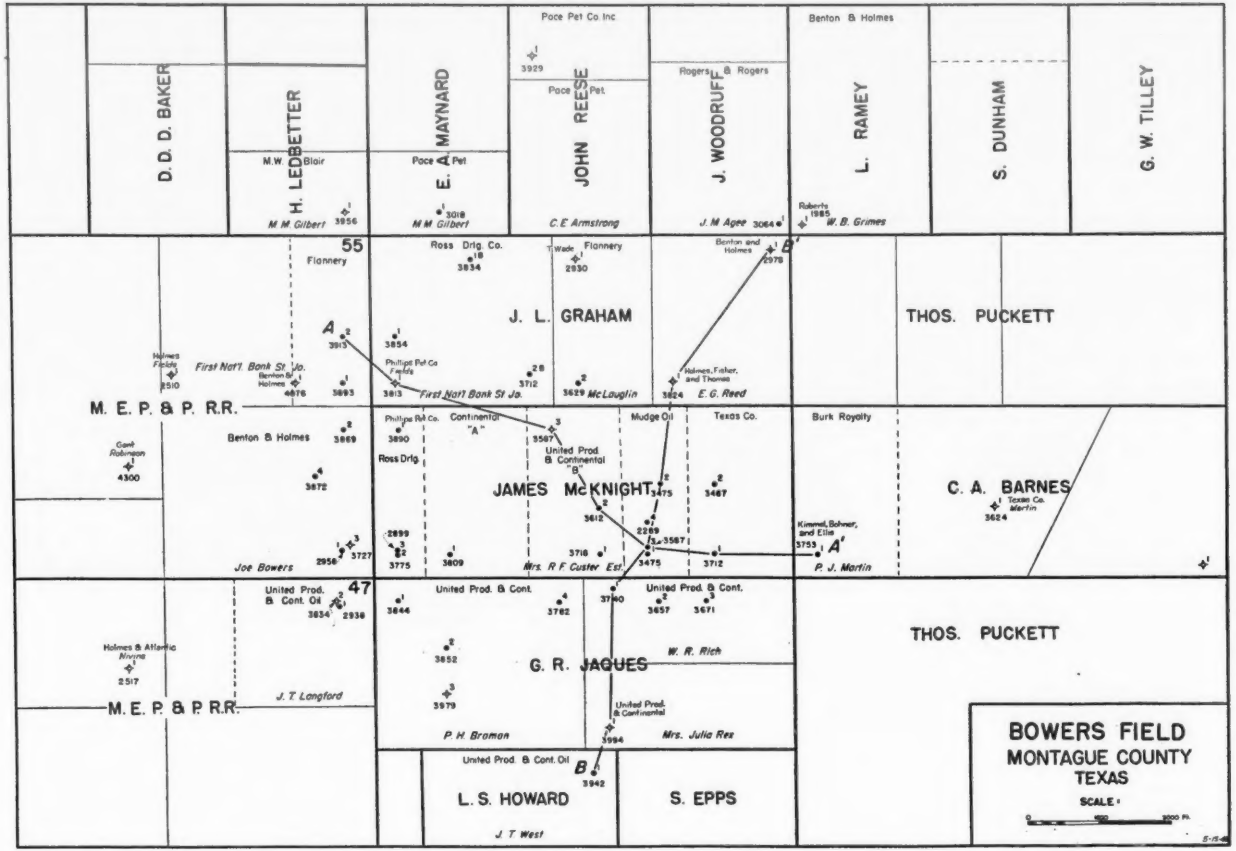

FIG. 2.—Reference map showing lines of cross section, wells, and total depths.

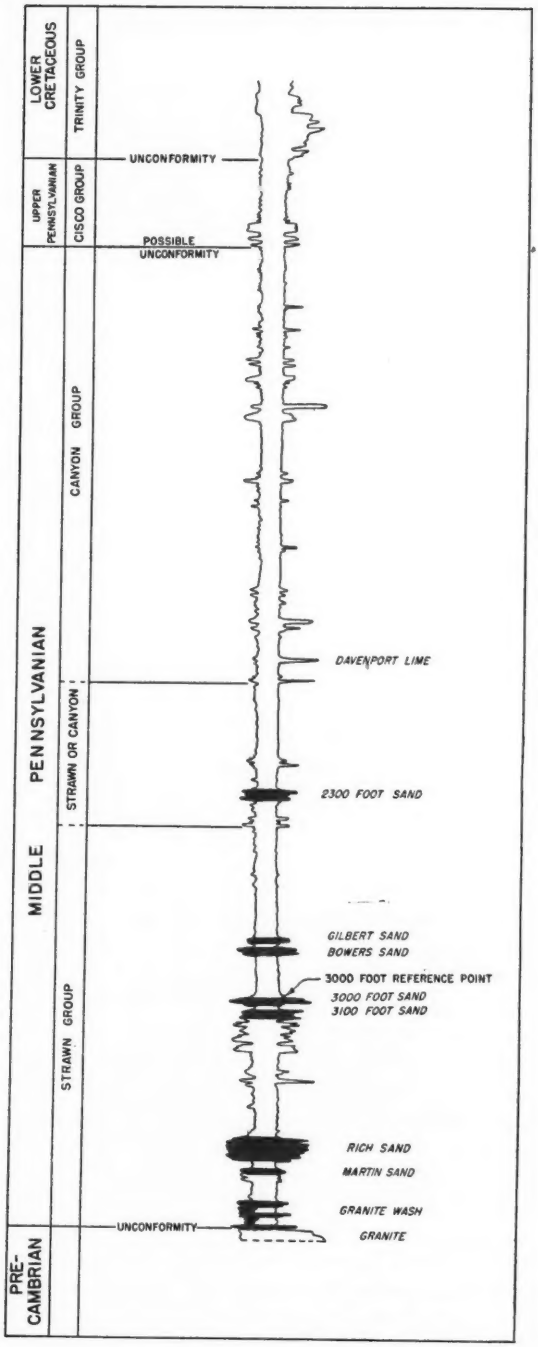

FIG. 3.—Composite section from electric logs.

sand" (Fig. 3), was added to the field's list of producing zones with an initial gauge of 2 barrels per hour through 10/64-inch tubing choke. A dry hole on the north approximately ½ mile, Holmes, Fisher and Thomas' E. G. Reed No. 1 (Fig. 2), and another approximately one mile east, The Texas Company's Martin No. 1 (Fig. 2), in addition to the already apparent lack of continuity of producing zones, materially retarded development in that part of the field. Development in the area on the west went on slowly, the irregularity of producing zones acting here also as a brake on drilling.

The latter part of August, 1940, The Mudge Oil Company completed its Custers No. 1, producing initially 91 barrels in 3 hours through ¼-inch tubing choke, flowing from the "Rich sand" at 3,430–3,475 feet total depth. This well was drilled as a north offset to the United Producers' and Continental's Rich No. 1, discovery well in the "Rich sand," and initiated a somewhat active development program in the eastern part of the field. As drilling progressed, new sands were found. In January, 1941, the United Producers and the Continental set pipe on the "Rich sand" in their Rich No. 2 (Fig. 2) and during the process of completion perforated casing at 2,998–3,021 feet to discover a new producing zone for the field, the "3,000-foot sand" (Fig. 3). This sand had previously been perforated in the Rich No. 1, but the results were indeterminate and for this reason discovery of this zone is ascribed to well No. 2.

By the end of February, 1941, another producing zone was added to the field's total. The United Producers' and Continental's Custers "B" No. 2 (Fig. 2) was brought in at this time, flowing 81 barrels in 3 hours through ½-inch tubing choke from perforations at 2,282–2,290 feet to open production in the "2,300-foot sand" (Fig. 3). In April of the same year, having found insufficient saturation in the "granite wash," the Ross Drilling Company set pipe and perforated at 3,084–3,100 feet in the Custers No. 2, thus discovering oil in the "3,100-foot sand" (Fig. 3), producing initially 35 barrels in 4 hours through ¼-inch tubing choke. To date, this constitutes the only development in this zone. Still another producing sand was added in July, 1941, by Kimmel, Bohner, and Ellis (Burk Royalty) in their P. J. Martin No. 1 (Fig. 2), located in the southwest corner of the C. A. Barnes Survey. Perforations at 3,532–3,540 feet yielded 84 barrels of oil and 5 barrels of water in 24 hours from the "Martin sand" (Fig. 3).

In November, 1941, the Pace Petroleum Company, Inc., completed its M. M. Gilbert No. 1 (Fig. 2), flowing an estimated 175 barrels per day from a sand at 3,008–3,018 feet total depth. This "Gilbert sand," or its equivalent, produced in the Phillips Petroleum Company's Custers No. 1 and has since been found productive in Rogers and Rogers' J.M. Agee No. 1 in the southeast corner of the J. Woodruff Survey. It should also be pointed out that a well drilled in the northeast corner of the J. L. Graham Survey by Benton and Holmes some years prior to the discovery of the Bowers field showed some saturation in this same "Gilbert zone." Casing was later set in this hole, but the results were not encouraging. However, there is some indication that the Rogers and Rogers and the

Benton and Holmes wells are located on structure separate from the Bowers field proper. Though the discovery of the "Gilbert sand" can not be ascribed to the Pace Petroleum Company, Inc., well, it would appear to be the first commercial completion in this zone.

Since its discovery, 45 wells have been drilled in and around the Bowers field. Of these, 32 have produced oil and 13 have been dry, a ratio slightly greater than one dry hole to three producers. No wells have produced gas alone. Accumulated production to the end of the first quarter of 1942 was 478,141 barrels, all of which has been produced under proration.

PHYSIOGRAPHY

The Bowers field lies entirely within the Gulf Coastal Plain physiographic province, in a part of that area defined by Hill[3] as the Western Cross Timbers. The surface is composed of reddish sands, sandy shales, and shales of Cretaceous age which support a heavy growth of jack oaks, but very little farming. Topographically, it is a region of considerable dissection, rolling to hilly in character. Elevations range from 900 feet to approximately 1,100 feet above sea-level. Drainage is toward the north into the Red River, the stream channels and arroyos traversing the area being characteristically deep, narrow, and steep-sided.

STRATIGRAPHY

Rocks of Lower Cretaceous, Upper and Middle Pennsylvanian, and probable pre-Cambrian age are present in the Bowers field and have been penetrated by the drill. The composite section (Fig. 3) shows the stratigraphy of the immediate area. Approximately 4,000 feet of sedimentary rocks overlie the granite in the Bowers field.

PRE-CAMBRIAN

The pre-Cambrian is here represented by a medium-grained pink granite which in some wells has had a weathered appearance. More than 100 feet have been penetrated in the Bowers field. On purely local evidence alone, the granite can only be said to be pre-Strawn in age. However, from the standpoint of regional position it has been referred to the pre-Cambrian.[4]

PENNSYLVANIAN

Strawn group.—Overlying the granite and separated from it by an angular unconformity of considerable magnitude are arkosic conglomerates and sands (0–180 feet thick), the "granite wash" zone of the field. These probably represent the marginal deposits of advancing seas and certainly much of the material here involved was derived from the granite hills and ridges in the immediate

[3] R. T. Hill, "The Geology and Geography of the Black and Grand Prairies, Texas," *U. S. Geol. Survey 21st Ann. Rept.* (1901).

[4] E. H. Sellards, W. S. Adkins, and F. B. Plummer, "The Geology of Texas," *Univ. Texas Bull. 3232, Vol. 1* (1933), pp. 47–49.

neighborhood. These deposits are ordinarily thinner over the higher granite areas, and are entirely lacking over the three granite "peaks" now known in the Bowers field (Figs. 4, 5, and 10).

The "granite wash" zone is not a single massive unit, but is ordinarily composed of many extremely lenticular arkosic beds separated by shales and sandy shales of varying thickness. In many places the "granite wash" zone contains practically clean quartz sandstones. There is considerable truth in the statement that vertical variation is scarcely more pronounced than lateral variation. The top of the "granite wash" is in some places very difficult to determine, because there is no clean-cut break and many of the sands considerably higher stratigraphically contain local arkosic material. This condition makes the "granite wash" zone an extremely hazardous correlation to use other than in very restricted areas.

The character of the succeeding deposits from the top of the granite and "granite wash" to the "3,000-foot reference point" (Fig. 3) is exceedingly variable, both in type and thickness (Figs. 4 and 5). Just below this reference point and extending downward as much as 300–350 feet is a zone of sandstones. Some of these sandstones are slightly arkosic and some are calcareous, and are locally associated with very black, carbonaceous shales. Correlation of the individual beds of this zone is virtually impossible throughout any great distance, though the zone itself can be carried far.

The isopachous map on the interval between the top of the granite and the "3,000-foot reference point" (Fig. 13) shows a definite and pronounced divergence away from the higher granite areas. Above this point divergence is limited, and sedimentation is normally very regular and uniform.

It is at present questionable as to how much of the whole sedimentary section overlying the granite in the Bowers field should be included in the Strawn group. Opinion seems divided as to which of the positions indicated on the composite section (Fig. 3) should be regarded as constituting the division between the Strawn and Canyon groups. In the Bonita field, Gill,[5] with reservation, has placed the top of the Strawn at the base of a sand closely correlatable with the lower position of the Canyon-Strawn boundary in the present paper. On the other hand, Clark[6] refers the base of the Canyon to a point corresponding with the upper position. From the standpoint of lithologic character and sequence, and pending more detailed investigation, it would seem that the Strawn-Canyon boundary in the Bowers field should more reasonably be placed at the base of the calcareous zone associated with the Davenport limestone: that is, at the upper position in the composite section (Fig. 3). Thus, the division would come at a point below which the sedimentation included much arenaceous material and very little of

[5] J. P. Gill, "Bonita Discovery, Montague County, Texas," *Bull Amer. Assoc. Petrol. Geol.*, Vol. 24, No. 10 (October, 1940), pp. 1838–39.

[6] G. C. Clark, "Rogers Pool, Montague County, Texas," *ibid.*, pp. 1836–38.

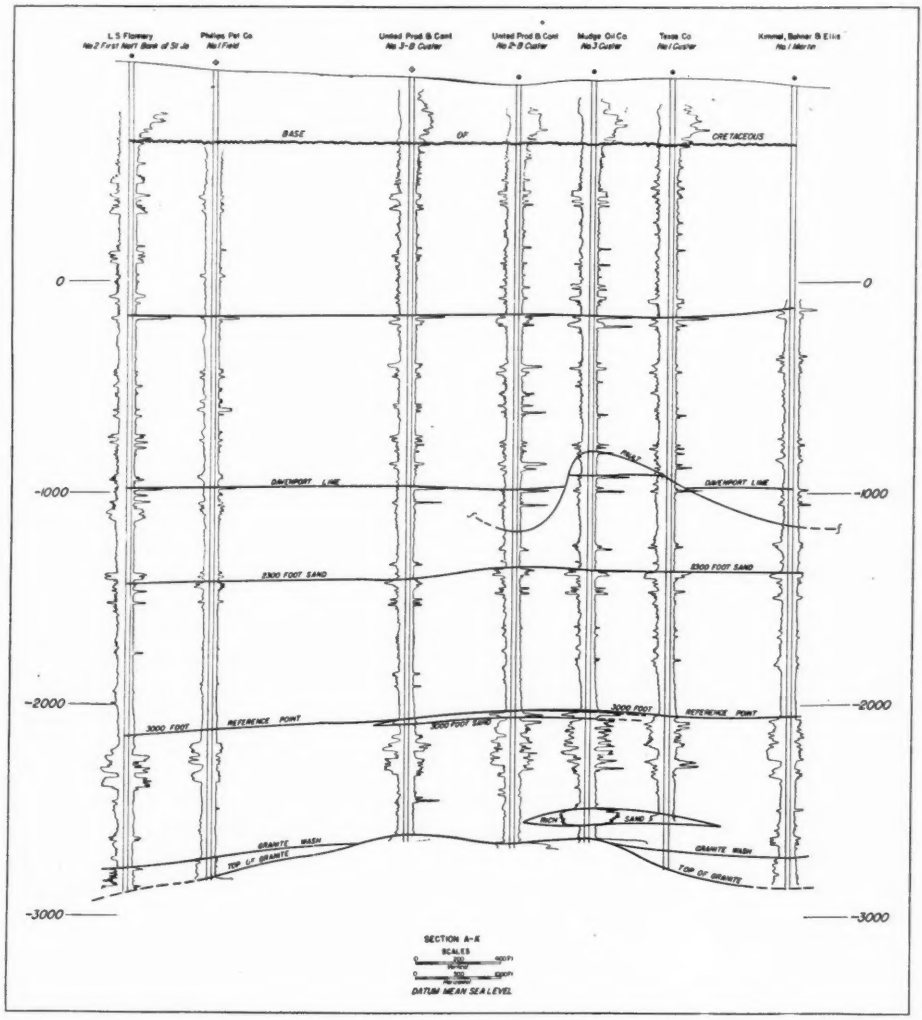

FIG. 4.—Cross section *AA'*. See Figure 2.

a calcareous nature, and above which limestones and calcareous deposition predominate over the sands.

If the Strawn group is extended upward to include the "Strawn or Canyon" zone of the composite section (Fig. 3), there are approximately 1,600–2,100 feet of sediments of Strawn age in the Bowers field. Seven of the eight producing

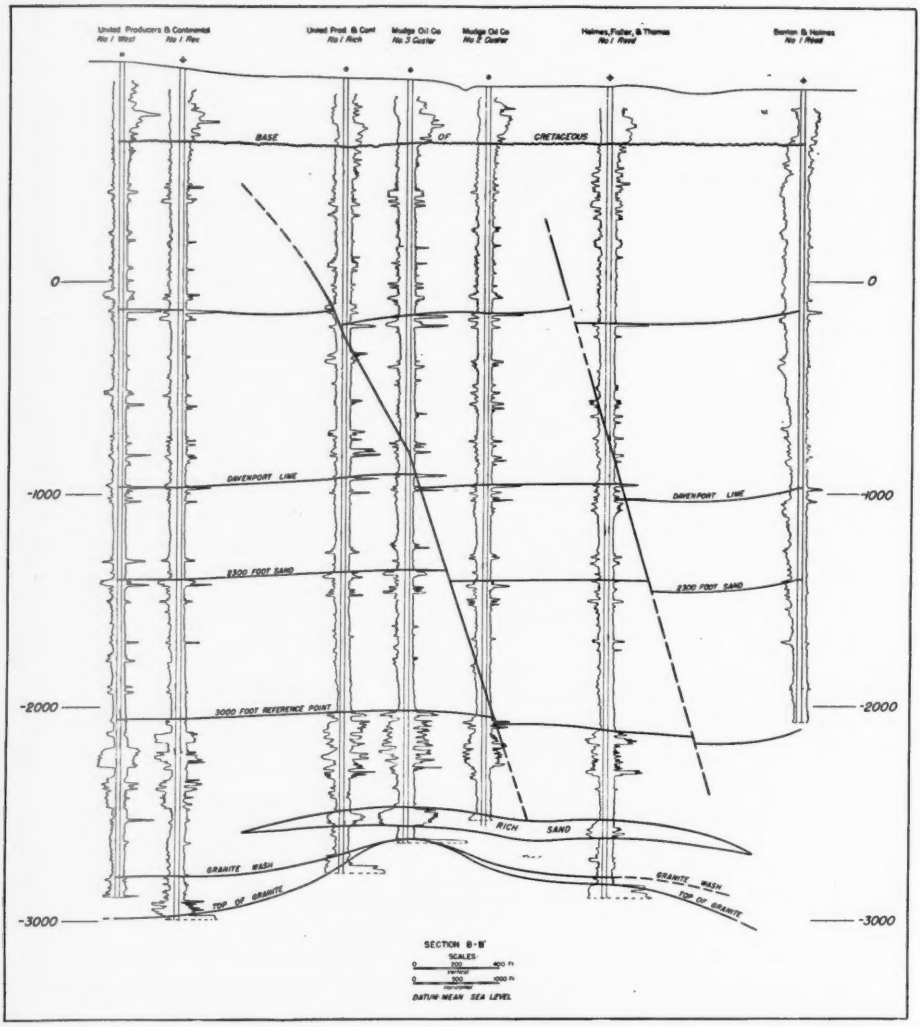

FIG. 5.—Cross section *BB'*. See Figure 2.

zones now known are definitely Strawn in age, while the age of the eighth, the "2,300-foot sand," is questionable.

Canyon group.—Excluding the debatable portion which has been labelled "Strawn or Canyon" in the composite section, the Canyon group has a thickness of approximately 1,400 feet in the Bowers field. This group consists of a succession

of limestones, calcareous shales, and shales, with some sands and sandy shales developed, though the latter are ordinarily of limited areal extent. Many of the limestones have local names and most of them are easily correlatable over wide areas even on driller's logs. The Davenport limestone and its associated calcareous zone are thought to represent at least a part of the Palo Pinto limestone. The division between the Canyon group and the overlying Cisco group is placed at the base of a well developed zone of cherty and conglomeratic sandstones, which may represent an unconformity. This division seems to have validity from a regional standpoint and corresponds with the point at which Clark[7] placed the base of the Cisco group in the Rogers and Rogers field (Fig. 1).

Showings of oil in the Canyon group have been reported at many localities, but other than the possible inclusion of the "2,300-foot sand," no oil has been produced from the Canyon in the Bowers field.

Cisco group.—Approximately 300 feet of conglomeratic and cherty sandstones, sandy shales, and shales make up the Cisco group in the Bowers field (Fig. 3). The overlying Trinity sands are separated from the Cisco group by a profound angular unconformity and it seems altogether probable that a much greater section of Cisco sediments was originally present in the Bowers field and was subsequently removed by erosion.

CRETACEOUS

Trinity group.—Two hundred seventy-five to approximately 450 feet of predominantly arenaceous sediments of the Trinity group of Lower Cretaceous age unconformably overlie the Cisco group of Upper Pennsylvanian age and form the surface in the Bowers field. The basal part of these deposits is very conglomeratic, with vari-colored chert a common constituent. Between the basal conglomerates and the top of the Cisco group proper, there are generally found 2–10 feet of yellow silt and silty shale. The occurrence of this bed is not restricted to the Bowers field as the writer has noted its appearance at the base of the Cretaceous throughout widely scattered points in western Cooke County where it overlies older Pennsylvanian formations. The widespread presence of the yellow silt and silty shale seems to suggest that it may represent a residual soil developed on the surface of the Wichita paleoplain prior to the deposition of the Cretaceous.

PRODUCING ZONES

In all, 8 separate zones of production have been opened in the Bowers field, all of which are either sand or conglomeratic sand. Of the 32 producing wells, completions on an approximate percentage basis are in the following order: "granite wash," 44 per cent; "Martin sand," 3 per cent; "Rich sand," 14; "3,100-foot sand," 3; "3,000-foot sand," 9; "Bowers sand," 9; "Gilbert sand," 9; "2,300-foot sand," 9. Together, the "granite wash" and the "Rich sand"

[7] G. C. Clark, *op. cit*

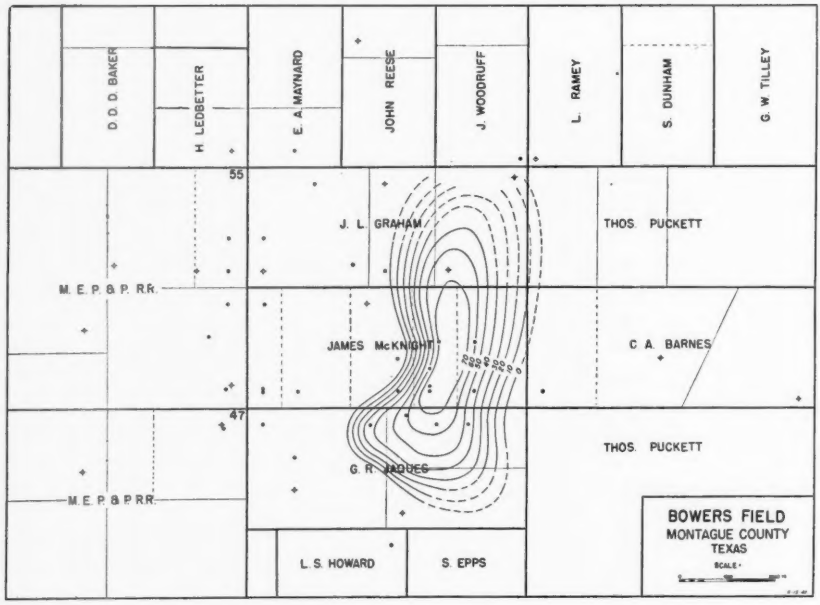

FIG. 6.—Isopachous map on "Rich sand." Contour interval 10 feet.

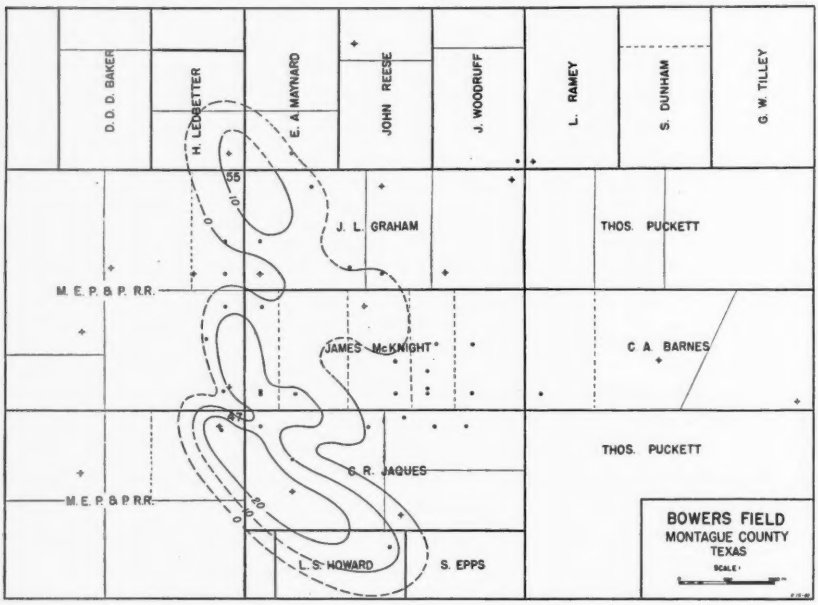

FIG. 7.—Isopachous map on "Bowers sand." Contour interval 10 feet.

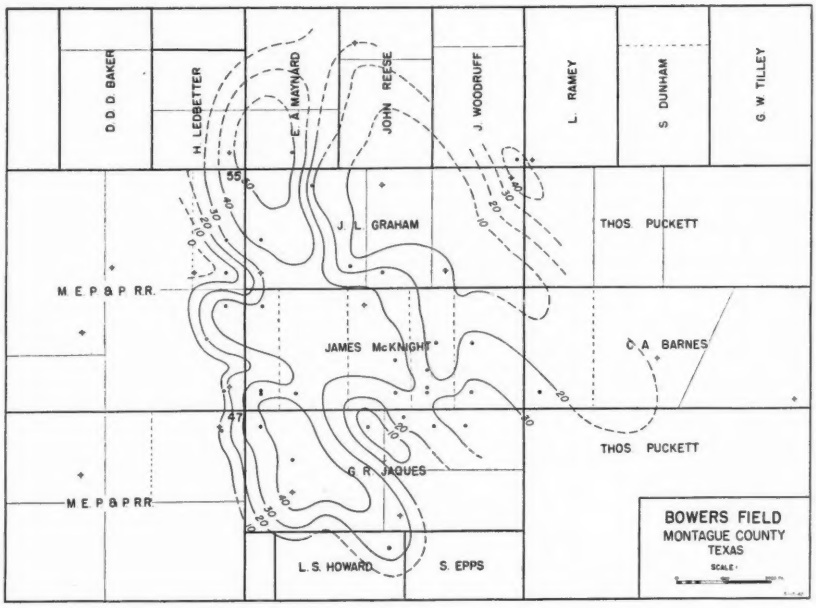

FIG. 8.—Isopachous map on "2,300-Foot sand." Contour interval 10 feet.

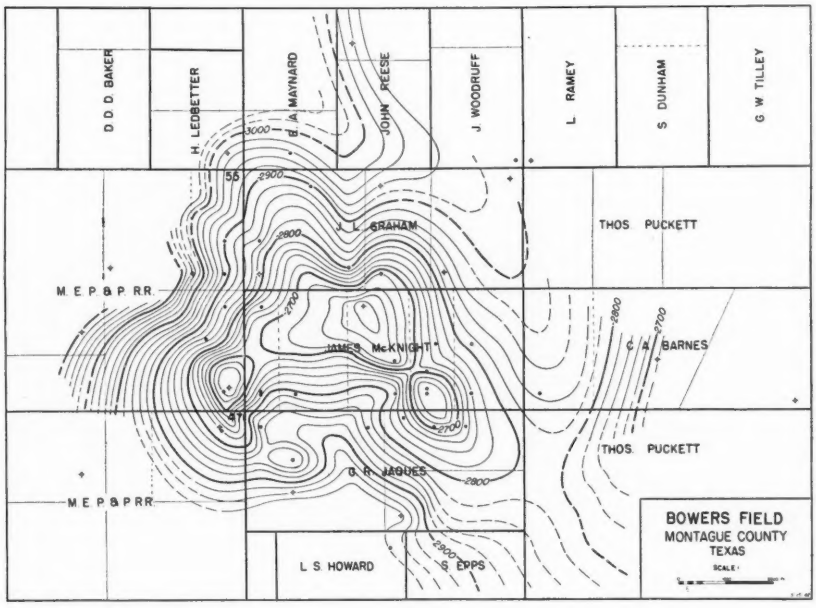

FIG. 9.—Structural contours drawn on granite. Contour interval 20 feet.

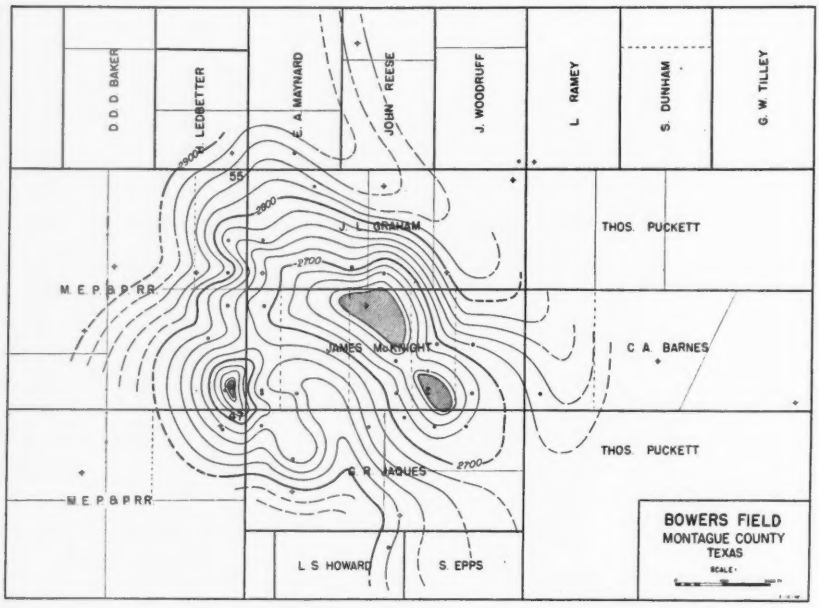

FIG. 10.—Structural contours on top of "granite wash." Contour interval 20 feet. Cross-hatching indicates absence of "granite wash."

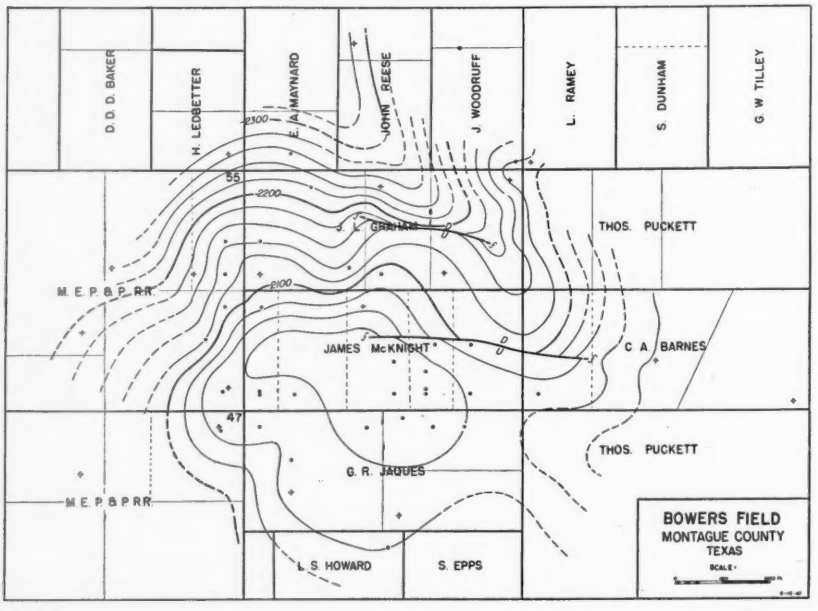

FIG. 11.—Structural contours drawn on "3,000-foot reference point." Contour interval 20 feet.

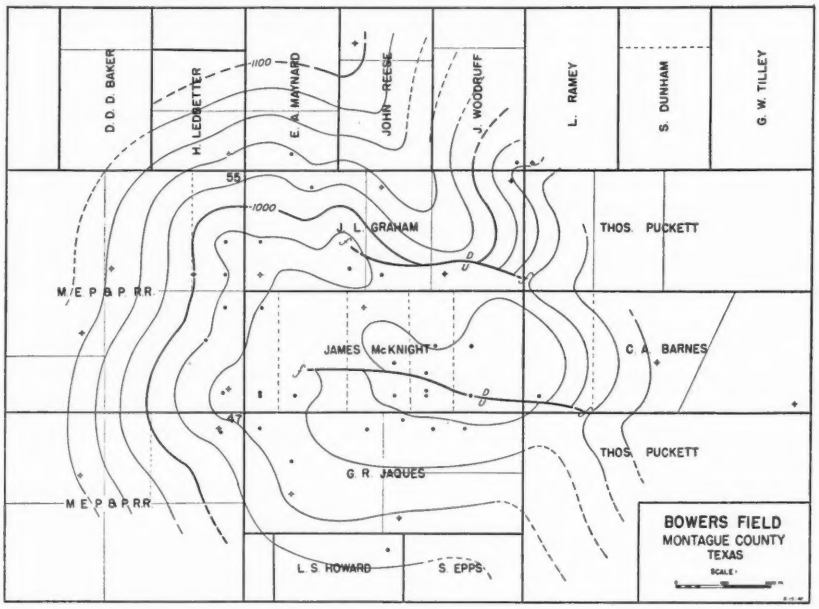

FIG. 12.—Structural contours drawn on top of Davenport limestone. Contour interval 20 feet.

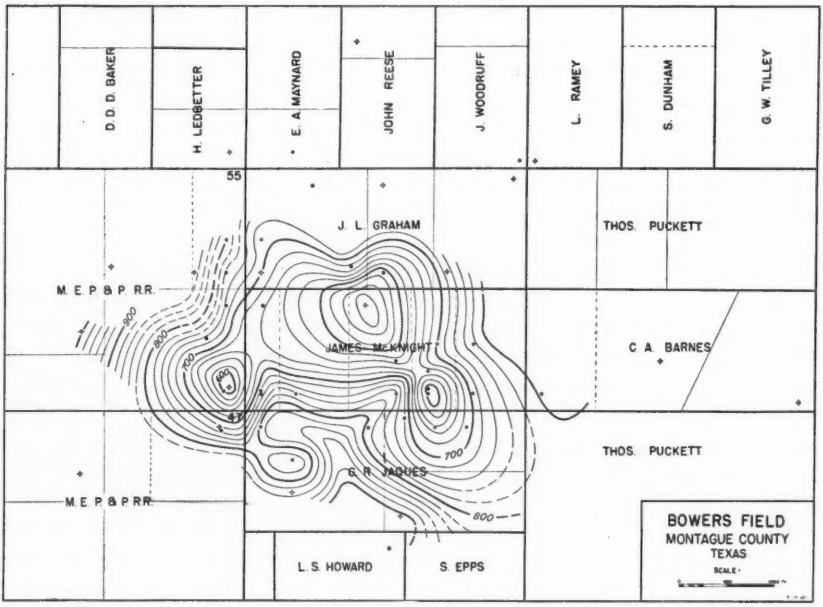

FIG. 13.—Isopachous map on interval between "3,000-foot reference point" and top of granite. Contour interval 20 feet for comparison with Figure 9.

account for only 58 per cent of the completions, but it is felt that at least 75 per cent of the oil ultimately recoverable will come from these two zones. The producing areas for most of the sands in the Bowers field have already been limited, with the possible exception of one or two of the more recent discoveries.

Gravity of oil produced in the Bowers field averages between 38° and 42° A.P.I. corrected, a relatively narrow range considering the number of producing zones and the diversity of depths from which the oil is obtained. On the whole, salt water in the field can not be said to constitute a serious problem. However, only a few of the producing zones are filled with oil to a degree approaching capacity, and, ordinarily, care must be exercised in drilling and completion.

In only two of the eight zones of production in the Bowers field can structure be considered the controlling factor in accumulation. Of the remaining six, some are doubtful, but in the greater number of cases stratigraphic variations appear to have the dominant rôle.

"Granite wash."—"Granite wash" oil in the Bowers field is produced from several different lenses within a zone which is exceedingly variable in thickness and producing behavior. As a general rule, the "granite wash" zone thins markedly or is entirely absent over the higher granite areas, and thickens a short distance from them (Fig. 4 and Fig. 5). Though there is considerable closure on top of the "granite wash" (Fig. 10), structural position alone is not a determining factor as many of the "high" wells have been dry in this zone; rather more important as controls on accumulation in the "granite wash" would seem to be individual stratigraphic variations within the zone itself.

"Martin sand."—The "Martin sand" produces in only one well in the field. There is at present insufficient control to permit an evaluation of its potentialities, but stratigraphy undoubtedly has a greater bearing than structure on production from this zone. Some question exists as to whether the "Martin sand" is correlative with the lowermost part of the "Rich sand." The writer, however, feels that it represents an independent development and occupies a lower stratigraphic position.

"Rich sand."—This sand reaches its greatest thickness in the Mudge Oil Company's Custers No. 3. Here a section of about 80 feet is developed, the major part of which is saturated sand with numerous shale laminations throughout. This zone thins within a short distance both westward and eastward, much of the upper part grading into sandy and silty shales and the main body becoming tight and calcareous. Reference to the cross sections (Figs. 4 and 5) plainly demonstrates this condition as they intersect in the Mudge Oil Company's Custers No. 3. The axis of this sand lens is nearly north and south as shown on the isopachous map (Fig. 6). In cross section the shape of the sand body appears to be convex upward, though there is no positive reference in its immediate range and it is thus rather difficult to determine. Its shape seems to preclude the possibility of its origin being due to channel fill and indicates a restricted type of bar deposition. Here also stratigraphic conditions seem to be the dominant factor in accumulation, though structure is undoubtedly an important factor.

"*3,100-foot sand.*"—At present, only one well produces from this zone, the Ross Drilling Company's Custers No. 2. However, it is probable that oil may be expected in the "3,100-foot sand" throughout a limited zone east of this well. Stratigraphy appears to be the controlling factor in production here.

"*3,000-foot sand.*"—The "3,000-foot sand" produces in a restricted area in the eastern part of the field where a limited amount of structural closure exists on the top of the sand. Approximately 20 feet of sand are present in the area in which it is productive. In cross section (Fig. 4), this zone disappears toward the west; eastward, it is extremely difficult to determine its course even though there is considerable electric-log control. Here it seems to intergrade and finally to fuse with a thick sand zone which farther west is subjacent to it. It appears that, in the Bowers field, accumulation in this zone is governed almost entirely by structural position.

"*Bowers sand.*"—Three completions have been made in the "Bowers sand." These include the discovery well in the Bowers field and its east and south offsets. The isopachous map (Fig. 7) shows a maximum development of slightly more than 20 feet and gives some indication of the extremely erratic behavior of this lens. On the east it is not present and it appears to be absent on the west, though control in this direction is incomplete. Its shape and limited areal extent suggest an origin related to offshore-bar deposition.

"*Gilbert sand.*"—Production from the "Gilbert sand" is obtained in three widely scattered wells, the Phillips Petroleum Company's Custers No. 1, the Pace Petroleum Company, Inc., M. M. Gilbert No. 1, and Rogers and Rogers' Agee No. 1 (Fig. 2). In section, the "Bowers" and "Gilbert" sands occupy positions which almost merge one into the other, and when both occur in the same well it is commonly difficult to determine where the division between them should come. The "Gilbert sand," where present, varies considerably in thickness and producing behavior. It is absent or only poorly represented in the greater part of the Bowers field. Like the "Bowers sand," it seems that stratigraphic conditions are the dominant factor in localizing accumulation in the "Gilbert sand" and that its origin is related to a similar type of deposition.

"*2,300-foot sand.*"—Like the "3,000-foot sand," the "2,300-foot sand" production is limited to an area in the eastern part of the field where a small amount of closure exists on the upthrown side of a fault. Unlike most of the producing zones in the Bowers field, this sand has considerable areal extent. The isopachous map (Fig. 8) shows the thickness variations within the field. An interesting aspect of this map is the close alignment between the areas of greatest thickness on the "Bowers sand" and the "2,300-foot sand" in the western part of the field. Structural position appears to be the dominant factor in controlling accumulation in this horizon.

STRUCTURE

The Bowers field is developed over an old buried ridge and is part of the Wichita Mountain uplift trend, to which it seems more closely related than to the

Red River arch. Structurally, it varies from a well developed anticline on the "granite wash" to an elongate, faulted anticlinal nose on the Davenport limestone and higher beds. A series of four structural maps is presented to demonstrate this condition (Figs. 9, 10, 11, and 12). The same contour interval has been used in each map so that a comparison of structural expression can easily be made.

A sufficient number of wells in the Bowers field have reached the top of the granite to permit the drawing of a generalized map (Fig. 9) on this old erosion surface. Attention is called to the three relatively high "peaks" and the low knob capping the ridge extending south and southeast from the "peak" in the southeast corner of Block 55, MEP and PRR Survey. Considerable relief exists on the granite to-day, and has existed in essentially its present expression throughout. In regard to this, reference should be made to the ispachous map (Fig. 13) drawn on the interval between the "3,000-foot reference point" and the granite. The contour interval used in this map is the same as that employed in the structural maps. After adjustment has been made for differential compaction, the one can be superimposed on the other with only minor variation in structural expression.

Three areas of closure appear on the "granite wash" (Fig. 10) surrounding the granite "peaks." The "granite wash" is absent over these three highest granite areas, this absence being indicated in general outline by cross-hatching. Contours on the "granite wash" retain much of the structural expression of the granite, though to a modified extent.

On the "3,000-foot reference point" (Fig. 11) only one broad area of limited closure remains and two minor faults have appeared. The displacement on these faults at this horizon is between 30 and 40 feet at a maximum, and both are down toward the north. Displacement increases materially higher in section until, on the Davenport limestone, a maximum of between 60 and 70 feet is present. Structural contours drawn on the Davenport limestone (Fig. 12) show an elongate anticlinal nose complicated by faulting with a possible 15 feet of closure against one of the faults. The presence of another fault, or an extension of the north fault, is suspected in the Pace Petroleum Company, Inc., M. M. Gilbert No. 1 as this well had an abnormally short Canyon section.

Origin of structure.—A consideration of the four structural maps (Figs. 9, 10, 11, and 12) and the isopachous map (Fig. 13) seems to point strongly to differential compaction as the predominant factor in explanation of the origin of the structure in the Bowers field. The increase in structural relief with depth is particularly suggestive, the closure in each case being within the limits imposed by experimental data.[8] This is especially true when it is considered that the overburden was once probably somewhat greater than it is at present. That some structural movement occurred along the Wichita Mountain trend is an accepted fact, but it is felt that the Bowers field received these adjustments as a unit with a minimum of differential structural movement.

[8] L. F. Athy, "Density, Porosity, and Compaction of Sedimentary Rocks," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 1 (January, 1930), pp. 1–24.

The origin of the minor faults in the Bowers field seems likewise explicable, in part at least, on the basis of stresses set up as a result of differential compaction. The faults now known are normal, are downthrown toward synclinal areas, and are in each case located in proximity to steep dips on the granite surface.

GEOLOGIC HISTORY

The column of Pennsylvanian sediments represented in the Bowers field is terminated at both ends by profound unconformities: an erosional contact with granite beneath and an angular unconformity with conglomerates of Lower Cretaceous age above. This column is further subdivided by one probable and one possible period of erosion and unconformity. The probable unconformity lies between Canyon and Cisco time, while the possible unconformity, for which there is virtually no local evidence, may be present in the intermediate zone between the Strawn and Canyon. Thus, known depositional history in the Bowers field began with seas advancing upon, and finally covering, the granite during Strawn time. That shallow water probably prevailed in the Bowers field throughout the greater part of the Strawn is evidenced by the high percentage of littoral and near-shore deposits present there.

As time progressed, the source of sedimentation was either farther removed or had more nearly approached base level. Sands were no longer discharged into the area in quantity and were replaced by the characteristically calcareous deposition of Canyon time. This period of deposition was succeeded, as it had been preceded, by sedimentation largely arenaceous in character. It is probable that only a part of the original deposits of this succeeding period remain today. It is possible even that other depositional periods followed with little or no interruption. In any event, on local evidence alone it is patent that uplift and a very long period of erosion intervened between the youngest Pennsylvanian formations represented in the Bowers area and the overlying conglomerates of Lower Cretaceous age. These conglomerates and overlying sands and shales were deposited as the Trinity seas advanced over the old eroded Pennsylvanian surface. Later, the area was again uplifted and these Lower Cretaceous deposits were in turn subjected to erosion, resulting in the dissected coastal-plain topography of the present.

On the basis of differential compaction, it must be assumed that the formation of the Bowers field structure was a continuous process, completed only when sedimentation finally ceased. The faults in the field cut strata of Canyon age and thus must be regarded as being at least no older than Canyon. Due to lack of control, it can not now be said whether rocks of Cisco and younger age in the field have been displaced by these faults, as is suspected.

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VOL. 27, NO. 1 (JANUARY, 1943) PP. 38-50, 6 FIGS.

STRATIGRAPHY AND STRUCTURE OF MOOSE MOUNTAIN AREA, ALBERTA[1]

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ABSTRACT

The Moose Mountain area, situated along the front range of the Canadian Rockies, 32 miles northwest of the Turner Valley oil field, Alberta, is characterized by a large domal structure that is approximately 10 miles long and 3 miles wide, and across which is exposed a series of beds that range in age from Cretaceous to Lower Carboniferous. This structural feature has been drilled at three separated locations, resulting in two very small wells and a failure. The tests were started only a few hundred feet above the Mississippian-Devonian contact. The dry hole, drilled by the McColl-Frontenac Oil Company, was carried about 2,700 feet below the top of the Cambrian; the other wells are deriving gas and oil from rocks of Devonian age. There are bituminous limestone zones in the lower part of the Devonian that are extremely porous where they crop out north and south of the Moose Mountain area; but in the McColl-Frontenac test, where these bituminous beds were encountered structurally high, the pore spaces and fractures were filled with secondary calcite.

INTRODUCTION

The Moose Mountain area is situated about 50 miles west of Calgary, and is roughly 32 miles northwest of the Turner Valley oil field, Alberta. Folding has produced a structure, known locally as the Moose Mountain dome, that is anticlinal or domal in shape. The axial plane of the fold strikes north-south and dips west; the axis pitches gently southward and northward from the apex on Moose Mountain. The exposed central part of this anticline is made up of massive limestone beds of Carboniferous age, flanked by progressively younger Mesozoic strata downward from the summit on each side of the anticline.

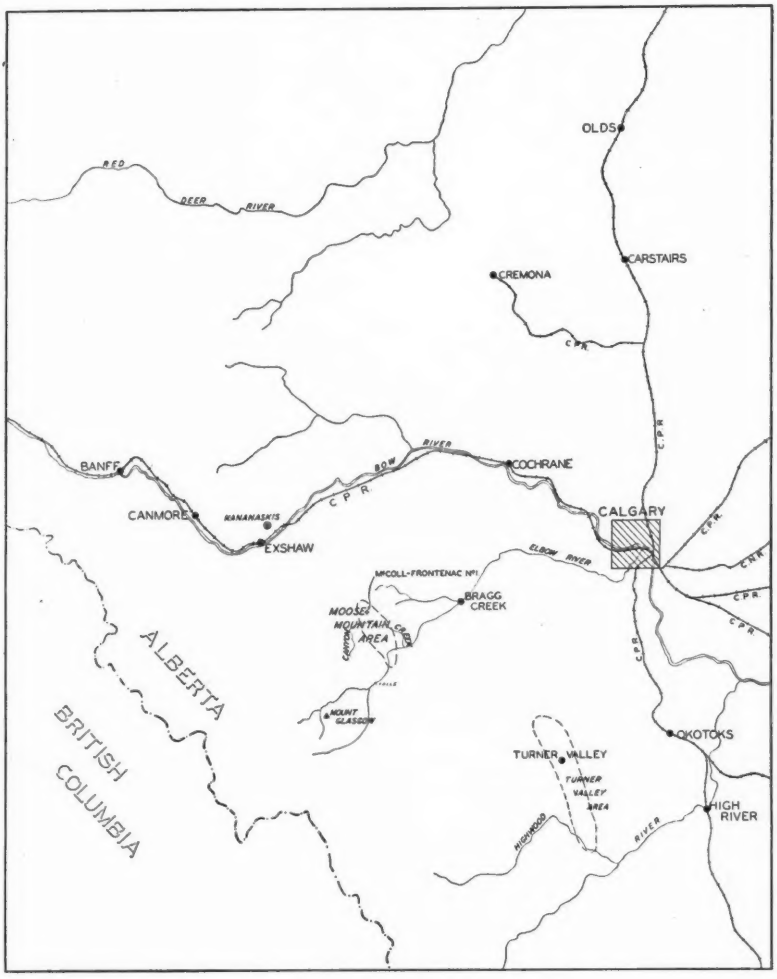
The area as a whole is very rugged; the major creeks run through precipitous canyons and deep valleys as they approach the larger drainage channels, but in their upper reaches some are characterized by relatively broad valley floors. Differential erosion along the Mesozoic-Paleozoic contact, where comparatively soft Jurassic shales are in contact with the Paleozoic limestones, has produced grassy valleys that stand out prominently within the area. In fact, exposures of Jurassic rocks are extremely rare, but in view of the characteristic vegetation along this zone the delimitation of the formation is not at all difficult. It has been noted, also, that practically all the creeks arising within the area have their source along the Jurassic-Cretaceous contact.

GEOLOGY

STRATIGRAPHY

The history of sedimentation in the Moose Mountain area is essentially the same as that of the regions to the north and south.[3] During Paleozoic time most

[1] Presented before the Association at Denver, April 24, 1942. Manuscript received, June 19, 1942.
[2] Geologist, McColl-Frontenac Oil Company, Limited.
[3] Theo. A. Link, "Alberta Syncline, Canada," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 5 (May, 1931), p. 491.



INDEX MAP

FIGURE 1

of the material deposited in this region was in the form of limestone, the process being interrupted finally by crustal movements that removed the Paleozoic seas and uplifted the adjacent regions that later supplied sediments to the relatively shallower marine waters of Triassic (?) and Jurassic times. Judged by the grada-

ERA	SYSTEM	SERIES	FORMATION	MEMBER	CHARACTER	THICKNESS IN FEET
MESOZOIC	CRETACEOUS	LOWER CRETACEOUS	BLAIRMORE		MASSIVE, GREY SANDSTONES, THICK ZONES OF SHALY, GREENISH SANDSTONE, AND A MASSIVE QUARTZITE AND CONGLOMERATE AT THE BASE.	1800
			KOOTENAY		INTERBEDDED DARK GREY SANDSTONES & SHALES WITH SEVERAL THIN SHALY COAL BEDS.	360
	JURASSIC		FERNIE		PAPER-THIN BLACK AND BROWN SHALES, SOME DARK SANDY SHALES & SANDSTONES.	260
PALAEOZOIC	CARBONIFEROUS	PENNSYLVANIAN	ROCKY MOUNTAIN QUARTZITE		MASSIVE, SILICEOUS, CHERTY LIMESTONE WITH INTERBEDDED SANDY LIMESTONES.	250
		MISSISSIPPIAN	RUNDLE		MASSIVE, GREY, FINE TO CRYSTALLINE, CHERTY, FOSSILIFEROUS LIMESTONE.	1250
			BANFF		FINE-GRAINED, THIN-BEDDED, BLACK-GREY, BUFF WEATHERING LIMESTONE AND CALCAREOUS SHALE.	625
	DEVONIAN		MINNEWANKA	UPPER MINNEWANKA	THERE IS A BLACK, PHOSPHATIC, 34-FOOT BED OF SHALE AT TOP OF THIS MEMBER, KNOWN AS EXSHAW SH. MASSIVE, HARD, CHERTY, DOLOMITIC LIMESTONE.	1054
				LOWER MINNEWANKA	LIMESTONE, MOSTLY GREY, FINE TO COARSE, INTERBEDDED BLACK, BITUMINOUS, POROUS ZONES.	1291
	CAMBRIAN				THIN-BEDDED, BUFF WEATHERING, LIMESTONES & MASSIVE, GREY LIMESTONES.	290
					MASSIVE, HARD, GREY, DOLOMITIC LIMESTONES.	1000+

STRATIGRAPHIC COLUMN
FIGURE 2

tional character of the sediments, the retreat of the Jurassic sea and the subsequent deposition of fresh-water Kootenay sediments were unattended by any pronounced regional diastrophism.

A stratigraphic column illustrating the formations in the Moose Mountain area is shown herein as Figure 2. The rocks exposed on the surface belong to the Carboniferous, Jurassic, and Cretaceous systems. The possibility that a pre-Jurassic zone exposed on Canyon Creek may be of Triassic age is discussed later in this paper. In view of the fact that the McColl-Frontenac Oil Company's test

penetrated strata older than those cropping out within the Moose Mountain area, the exposed sections of these pre-Mississippian rocks were studied in nearby places where detailed measurements could be made.

CRETACEOUS

The youngest strata discussed in this paper belong to the lower part of the Cretaceous system, falling within the Blairmore formation. This formation has a thickness of approximately 1,800 feet in the Moose Mountain area; it is characterized by massive beds of grayish sandstone separated by relatively thick intervals of gray and greenish gray, shaly sandstones and sandy shales. A conglomerate, averaging about 10 feet in thickness, and composed of small, semi-angular, vari-colored cherts, occurs about 250 feet below the top of the formation. A massive bed of quartzite, generally underlain by a coarse conglomerate, occupies the basal portion of the formation. This member, referred to as the Blairmore conglomerate, ranges in thickness from 15 to 30 feet; it is made up of chert and quartzite, and serves as an excellent marker bed in geologically mapping areas in which it is present.

There is no evidence of an angular unconformity between the Blairmore formation and the underlying Kootenay formation, although there is ample evidence to indicate an erosional contact between these units. The Kootenay formation is approximately 360 feet thick in the Moose Mountain area, and is composed of interbedded dark gray sandstones and shales, with several thin, shaly coal seams occurring throughout the formation.

JURASSIC

A massive black-brown sandstone, 25 to 60 feet thick, separates beds that are definitely Kootenay in age from the typical, paper-thin, brown and black shales of the Fernie formation. These massive beds have been classified as Kootenay by Cairnes,[4] but he points out that some fossils have been found in the lower Kootenay beds that are probably of Jurassic age. The writer was unable to find evidence that contributed to the age determination of the massive brown sandstones in question, and it has been assumed for the purposes of this paper that they represent a transition between the Jurassic and Cretaceous systems in this area, and as such have been considered arbitrarily as a part of the Fernie formation. This formation is approximately 260 feet thick in the Moose Mountain area. It consists of thin, evenly bedded, brown, sandy shales and several narrow beds of yellowish brown, fine-grained sandstone.

TRIASSIC

P. S. Warren,[5] in describing a 3,400-foot section of Spray River (Triassic) strata located in the Banff area, refers to one 64-foot zone near the base as being, "black, fine-grained, calcareous shale interspersed with beds of dark grey to

[4] D. D. Cairnes, *Geol. Survey Canada Mem. 61*, pp. 31 and 32.

[5] P. S. Warren, *Geol. Survey Canada Mem. 153*, p. 41.

black, fine-grained argillaceous limestone." There is a 50-foot zone on Canyon Creek, lying on what is believed to be an erosional surface at the top of the Carboniferous section, that closely fits the description quoted. In view of the fact that rocks of Triassic age have never been reported from the Moose Mountain or adjacent areas, a very thorough study of this Canyon Creek outcrop was made. A careful search did not reveal the presence of fossils, and no evidence substantiating the possibility that this section is the correlative of the Spray River formation could be discovered. In other parts of the area, at the observed contact between the Mesozoic and Paleozoic rocks, this section is not present. On Canyon Creek, about 4 miles upstream from the afore-mentioned exposure, on the west flank of the Moose Mountain fold, the contact is plainly visible, and at this locality the typical black and brown Fernie shales overlie the Carboniferous limestones.

CARBONIFEROUS

Pennsylvanian.—The upper part of the Carboniferous section in the Moose Mountain area is characterized by a zone, approximately 250 feet thick, that is predominantly calcareous; the rocks, however, are very siliceous, fine-grained, mouse-colored, weathering bone-white and gray with a pinkish tinge. Intercalated with these rocks are platy beds of fine-grained, sandy, brownish gray, buff-weathering limestones, and near the top there is commonly a hard, whitish gray, limestone breccia. This zone is believed to be the Rocky Mountain quartzite and, as such, is Pennsylvanian in age. On Canyon Creek, where the Triassic (?) outcrops referred to earlier in this paper are located, there are associated with the afore-described rocks several feet of soft, dark brown, calcareous sandstone that give off a strong odor of petroleum; and here too is a 20-foot bed of extremely hard, pinkish gray, massive, arenaceous dolomite which, like the petroliferous sandstone mentioned, was not found to be a part of the Upper Carboniferous in other parts of the area.

The so-called Rocky Mountain quartzite of the Moose Mountain area does not bear any resemblance to the Rocky Mountain quartzite that crops out immediately north of Canmore (Fig. 1), where it occurs as a true quartzite. At Moose Mountain these uppermost Carboniferous beds are distinctly different from those stratigraphically below, although the change is gradual without any evidence of a hiatus. In view of the lithologic differences between this upper zone and the underlying limestones, the uppermost beds are assumed to be contemporaneous in age with the true Rocky Mountain quartzite. This formation caps the highest mountain peaks within the area; its position on top of Moose Dome is depicted in Figure 3. Aside from the location on Canyon Creek, the Rocky Mountain quartzite is best exposed on a small tributary to Coxhill Creek, and on the west slopes of a limestone ridge near the falls in Elbow River. At the latter location there are at least two erosional unconformities within the formation, separated by only a few feet of strata. Here also, as in other parts of the area, well formed ripple marks and rain prints are common to certain zones in

this Pennsylvanian member, pointing strongly to the possibility that the deposits are of the near-shore type.

There is no evidence of an angular unconformity between the Mesozoic and Paleozoic beds, although it is probable that a hiatus as great as the one herewith represented precludes the possibility of conformity at this contact. A relatively slight angle of unconformity could be present; but since there are only two or three places where the Paleozoic-Mesozoic contact is visible, and even at these places the zone is traceable for only a few feet, there is very little chance of detecting an angular difference. There is definite evidence, however, that the top of the Rocky Mountain quartzite is marked by an erosional unconformity.

Mississippian.—Underlying the Rocky Mountain quartzite is a section, about 1,250 feet thick, of fine- to coarse-grained, massive, gray fossiliferous limestone that has been determined to be Mississippian in age. This formation, known as the Rundle, being very resistant to erosion in comparison with the Mesozoic beds, makes up the more prominent mountain ridges and peaks within the area. The Rundle formation is characterized by numerous chert zones, white and black in color, with the latter predominant near the base. Fossils are plentiful in many zones throughout the formation, the prevailing types being crinoids, corals, bryozoans, and brachiopods. The lithological and chemical properties of some of the Rundle members are remarkably consistent along the strike; as a result there are zones, invariably occurring as vertical cliffs, that can be followed for considerable distances, thus greatly facilitating the structural mapping. In areas where Rundle exposures are more or less isolated it is difficult to determine, from the physical characteristics of the rock, the stratigraphic position of the outcrop. In other words, the formation as a whole is very much alike from top to bottom, and consequently it is impracticable to select a marker-bed in one part of the area that is applicable in mapping other near-by sections of Rundle limestone.

The main producing zones in the Turner Valley area are about 150 feet and 400 feet below the top of the Carboniferous, which, according to most geologists who have worked in that area, are within the Rundle limestone. Aside from the porous, petroliferous zone referred to on a previous page as having been a part of the Rocky Mountain quartzite formation, no zones that one could designate as having been source beds, or as at one time having been reservoir beds, were found within the Rundle formation of the Moose Mountain area. However, it is possible that oil did not migrate in these beds either before or after the area was uplifted for reasons bearing upon local structural conditions; but there are several relatively narrow zones, particularly within a few hundred feet from the top of the Rundle formation, where the rock is sufficiently porous to hold oil if all other factors for its accumulation were present. At several localities within the area there are caverns in the limestone, in some places extending more than 300 feet into the rock, that were formed by circulating solutions.

The contact between the Rundle formation and the underlying Banff for-

mation is in many places obscured by talus. The evidence available at one or two places within the area, however, leads to the conclusion that there is an erosional unconformity between these Mississippian formations. The upper part of the Banff formation is made up of dense, cherty, black-gray, hard limestone, grading downward to thin-bedded, fine-grained, buff-weathering, in many places platy, arenaceous, calcareous shale. The total thickness of the formation is probably about 625 feet. There is a paucity of fossils in that portion of the Banff formation exposed in the area, although in one narrow zone a great many small brachiopods, predominantly of the genus Camarotoechia, were collected. P. S. Warren,[6] in discussing the fauna collected from the Banff formation at the type locality, states that the fossils are similar in age to those found in the Kinderhook shales of the Mississippi Valley and in the Madison limestone of Wyoming.

DEVONIAN

The oldest rocks exposed in the Moose Mountain area belong to the upper part of the Banff formation. Prior to the commencement of McColl-Frontenac Oil Company's test, the writer studied the Devonian and Cambrian rocks that are exposed in adjacent areas in order to determine the nature of the pre-Banff formations, and in particular to estimate the thicknesses of these older beds. Rocks of this age are well exposed on the Banff highway, at a point very close to Kananaskis about 18 miles northwest of Moose Mountain. This exposure is depicted in Figure 4; here, as elsewhere in this part of the Rocky Mountains, the Devonian rocks have been grouped under the name Minnewanka, and this formation has in turn been divided into the upper Minnewanka and lower Minnewanka. The former member was found to be 1,046 feet thick at Kananaskis. It is a massive, gray, medium-grained, mottled, dolomitic limestone. It is extremely hard, and consequently so resistant to erosion that it commonly occurs as the more precipitous sections of the high mountains along the Front Range of the Canadian Rockies west and southwest of the Moose Mountain area.

Separating these Upper Devonian rocks from the Banff formation is an interval of black, phosphatic shale that has a thickness of 34 feet at its type locality near Exshaw, Alberta (Fig.1). This black shale is an excellent horizon marker in nearly all the deep tests drilled in the prairie portions of the province, and it is referred to locally as the Exshaw shale. It is conformable with the overlying and underlying limestones; and, on the basis of Devonian fossils, it is herein considered as a part of the Minnewanka formation.

[6] P. S. Warren, *Geol. Survey Canada Mem. 153*, p. 24.

FIG. 3.—View on Canyon Creek, showing section across Moose Mountain anticline. Contact between Rocky Mountain quartzite and Rundle formation, and between Rundle and Banff formations, indicated by black lines. Test site in right foreground was abandoned without drilling.

FIG. 4.—View near Kananaskis, Alberta.

FIG. 6.—View looking west up Canyon Creek across Moose Mountain fold. *A* indicates location of Moose Oils No. 2 well; *B* shows test site of Canadian Royalties No. 1; *C* marks junction of Canyon and Sulphur creeks; Moose Oils No. 1 is less than ½ mile, and McColl-Frontenac's Moose Mountain No. 1 less than 3 miles, up Sulphur Creek from this point.

FIG. 3

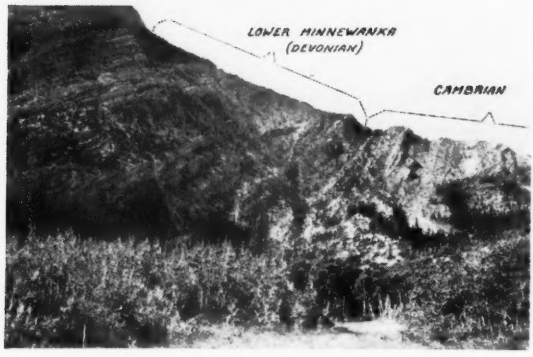


FIG. 4

FIG. 6

In addition to the section of Minnewanka rocks exposed at Kananaskis, there is a very good exposure of this formation in the vicinity of Glasgow Mountain, 13 miles southwest of Moose Mountain. At these localities the upper and lower Minnewanka are conformable, and in general the members that are stratigraphically equivalent are also lithologically similar at both places. The lower Minnewanka is composed of fine-grained, gray and brownish gray dolomitic limestones, with beds of coarsely crystalline limestone, and relatively thick zones of black, bituminous, porous, arenaceous limestone. It has a measured thickness of 1,291 feet, making an overall thickness of 2,337 feet for the entire Minnewanka formation.

At Moose Mountain, in the McColl-Frontenac Oil Company's test, 2,234 feet of this formation was penetrated. At the outcrop, both at Kananaskis and at Mount Glasgow, there are several zones in the lower Minnewanka that are very porous, which may be due to surface and near-surface leaching. These zones were recognized in the company's test at Moose Mountain, but the pores and vugs in the limestone were completely filled with calcite. Since the Devonian rocks are becoming increasingly more important as possible oil reservoirs in Alberta, a detailed description of the Minnewanka formation exposed at Kananaskis is here submitted. These measurements are from the top to the bottom of the formation.

	Feet
Thin-bedded, jet black, phosphatic shale	34
Covered	45
Massive, gray, medium-grained, mottled, dolomitic limestone	885
Finely bedded, arenaceous, light gray, dolomitic limestone	90
Buff weathering, fine-grained, gray, very hard quartzite	2
Light gray, quartzitic dolomite	1
Very thin-bedded arenaceous dolomite	148
Siliceous limestone, grading into light gray, fine-grained limestone	10
Highly cavernous, black, bituminous, fine-grained limestone	48
Dark, fine-grained, bituminous limestone	29
Massive, light gray-weathering, brownish gray, coarse-grained, saccharoidal limestone	83
Very porous, coarse-grained, gray limestone, containing corals and brachiopods	20
Coarse-grained, light gray limestone, has some porosity	80
Very porous calcareous zone, vugs up to one foot in diameter	2
Massive, coarse-grained, grayish brown, light gray-weathering limestone	70
Porous zone of limestone	4
Very finely cross-bedded, light gray, coarsely crystalline limestone	10
Coarse-grained, light gray, massive limestone	15
Black, bituminous limestone with some porous zones	92
Hard, dense, black, bituminous limestone	6
Covered	20
Very fine-grained to coarse, dull black, bituminous limestone. Vugs up to 7 inches in diameter, calcite-filled, give porous appearance	315
Dull black, bituminous limestone, large corals	168
Massive, dull gray, granular, bituminous limestone. Freshly broken pieces give off odor of petroleum	60
Platy, arenaceous, dull gray to black limestone	8
Very thin-bedded, light gray limestone	3
Covered	89

A summary of the Minnewanka section penetrated by the McColl-Frontenac Oil Company's test at Moose Mountain, tabulated downward from the Banff Minnewanka contact, is here given.

	Feet (Approx.)
Shale, very dark gray (poor samples), probably Exshaw shale	10
Limestone, medium gray, in part dolomitic	25
Gypsum, with stringers of limestone	40
Dolomite, gray, in part oölitic, some gypsum	140
Limestone, dolomitic, gray, finely crystalline	45
Dolomite, brownish gray, a little gypsum near top	200
Limestone, brownish gray	220
Dolomite, grayish buff, 50-foot oölitic zone 200 feet from base	600
Limestone, dark gray to buff	80
Dolomite and dolomitic limestone, buff-gray and dark brown	190
Limestone, fine-grained, brownish black, fossiliferous; considerable calcite in separated zones	684

CAMBRIAN

Underlying the lower Minnewanka section at Kananaskis is a zone of interbedded massive, gray, dolomitic limestones and brownish gray, thin-bedded, glauconitic, arenaceous limestones, that total about 290 feet in thickness. It has been a matter of debate among some local geologists whether this zone is Devonian or Cambrian in age. Some years ago P. S. Warren[7] expressed the opinion that a zone occurring at the base of Sulphur Mountain near Banff, and having about the same thickness and stratigraphic position as this zone, is equivalent to the Ghost River formation, which he placed questionably in the Devonian system. Recently some trilobite fossils were discovered[8] near the top of the 290-foot zone at Kananaskis that dates it as Middle Cambrian in age. In view of the fossil evidence, and on the basis of lithology, the writer is inclined to consider this interval as a unit, and as such has assumed that all of it is Cambrian in age. This classification can not be considered as indicative that the Ghost River formation, mentioned earlier, is of Cambrian age. It is possible that there are no rocks in the Kananaskis section equivalent to the Ghost River beds of Banff. On the other hand, it may be contended that the interval from the base of the lower Minnewanka down to the stratum where the Cambrian trilobites were discovered, a stratigraphic thickness of about 90 feet, is equivalent to the Ghost River formation. However, if the Ghost River formation is of Devonian age, and there are apparently some reasons for believing that it is, it is quite likely that since the beds are well exposed throughout this interval at Kananaskis some evidence of a hiatus could be detected across the 90-foot zone in question, indicating a break in time between Devonian and Middle Cambrian deposition.

At Moose Mountain, in the McColl-Frontenac test, this pre-Minnewanka interval was found to be 271 feet thick. In view of the fact that the contact between the Minnewanka and the underlying zone is exposed within a very limited area at Kananaskis, and since this contact is covered in the area near Mount Glasgow, the presence or absence of an angular unconformity in this part of the section could not be determined.

[7] P. S. Warren, *Geol. Survey Canada Mem. 153*, p. 13.

[8] H. H. Beach, *Geol. Survey Canada*, personal communication.
F. McKinnon, Geological Department, University of Alberta, personal communication.

Immediately below the afore-mentioned Middle Cambrian section, and apparently conformable to it, is a thick interval of dark gray, hard, in part oölitic, dolomitic limestone, with some beds of finely crystalline, dark gray, hard, somewhat siliceous limestone. The writer has examined only the upper 1,000 feet of this interval at Kananaskis. In the McColl-Frontenac Oil Company's test at Moose Mountain the top of this zone was encountered at 2,765 (plus 3,325) feet. The description of the surface outcrops applies to the rocks penetrated in the test, except that some black, calcareous shales were encountered at about 3,000 feet, and some green talcose, pyritic shales were drilled from 3,640 to 3,718 feet. The test was abandoned at 5,200 feet, in rocks essentially the same as those immediately below 2,765 feet, except that a very high percentage of calcite was present in the limestone section penetrated near the bottom of the hole. A review of the available literature regarding the Cambrian rocks of the Canadian Rockies did not reveal sufficient information to select a correlative Cambrian section to this interval of limestone and shale. According to Shimer[9] there is a section below the Ghost River formation near Lake Minnewanka, Alberta, that he refers to as the Castle Mountain group. The description of this interval closely approximates the section drilled below 2,765 feet in the McColl-Frontenac Moose Mountain test. Shimer dates this section at Lake Minnewanka as Middle Cambrian.

STRUCTURE

REGIONAL STRUCTURE

A cross section of the Rocky Mountains in this part of Canada, made at right angles to the general trend of the ranges, would reveal a structure that is roughly a synclinorium, broken by folds and thrust faults. In nearly all instances the axial planes of the folds and the fault planes dip west. The degree of folding varies greatly from place and place, so that in any such cross section there is likely to be a variety of folds that range from gentle symmetrical flexures to highly unsymmetrical, tightly folded anticlines and synclines. At a few places along the Front Range of the Rockies in the west-central part of Alberta there are some structures that appear to be more or less symmetrical, that are gently folded and relatively free from faulting of any description. Most of those that are anticlinal are too small, or the possible oil-bearing rocks are at too great a depth to make them commercially attractive. There are exceptions, such as the Moose Mountain anticline, however, where comparatively large, more or less gently folded structures stand out prominently, with a minimum amount of disturbance along the flanks of the fold.

LOCAL STRUCTURE

The strata involved in the movements that occurred in the Moose Mountain region varied greatly from the point of view of competence. The near-surface

[9] H. W. Shimer, "Upper Palaeozoic Faunas of the Lake Minnewanka Section, near Banff, Alberta," *Bull. 42 Geol. Ser. 45, Contributions to Canadian Palaeontology* (May, 1926), p. 23.

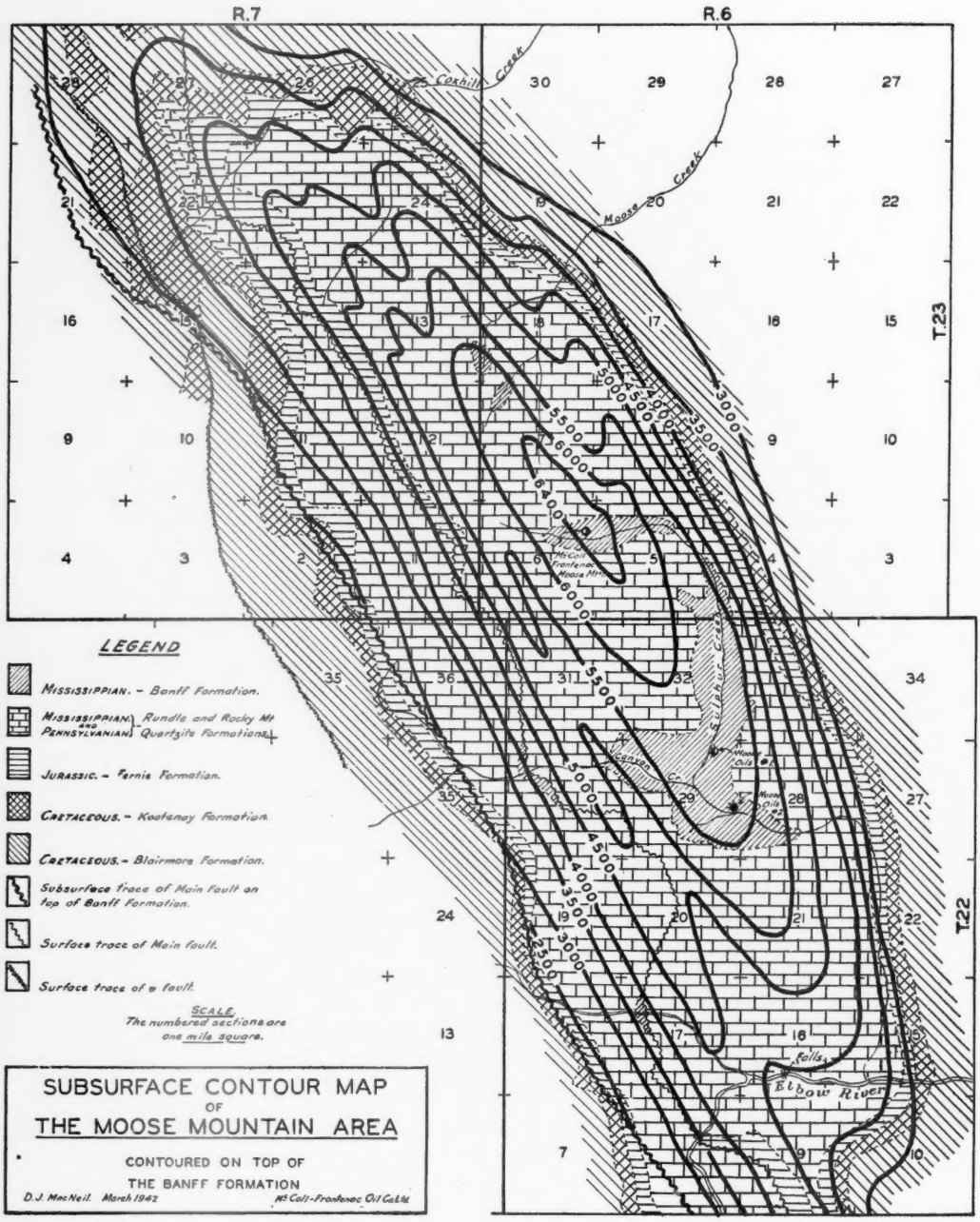


FIG. 5.—Structure map.

beds were relatively incompetent, while those below were composed of the competent Paleozoic limestones. As would be anticipated under such circumstances, the folds in any particular stratum are not necessarily reflected in the underlying or overlying strata; nor would it be expected that a fault penetrating these beds of varying hardness would cut through the strata at a uniform angle. It was observed, for instance, that folding in the comparatively soft Kootenay and Fernie strata is not necessarily reflected in the more massive underlying beds.

The main feature of the area is the Moose Mountain anticline, which is in reality an elongate dome that has been sufficiently eroded to expose the Paleozoic strata for a distance of about 10 miles along the long axis, and for about 3 miles across the shorter axis. The west flank has a west-dipping fault, trending roughly 35° west of north, which is more or less parallel with the long axis of the fold, and which crops out about one mile west of the apex. In view of the fact that this fault plane dips westward it does not affect the normal sequence of the stratigraphic column anywhere east of the point where it comes to the surface; its average throw is 3,000 feet. At a point about midway between the surface trace of this fault and the apex of the anticline is a tightly folded zone that may be faulted. This zone, which is about 2,700 feet west of the apex, can be closely studied on the north and south slopes of Moose Mountain. Northward from Moose Mountain this zone becomes more complex, turning into several northward plunging anticlines and synclines.

In contrast to the faulting and folding on the west limb of the main anticlinal feature, the Paleozoic rocks on the eastern side of the axis are relatively undisturbed. There are several folds in the Blairmore (Cretaceous) formation on this eastern flank of the anticline, but no evidence of faulting throughout this zone could be detected. The highest structural point on the fold is in the NE. $\frac{1}{4}$ of Sec. 6, T. 23, R. 6. The axis dips northward from here at about 5° and southward at about 4°; the beds on the west limb have an average dip of 38° and those on the east flank are inclined on the average at about 33°. The McColl-Frontenac Oil Company drilled its test on the crest of the Moose Mountain dome, approximately 1,500 feet south of the apex of the fold. It is believed that the location adequately tested the higher part of the structure. The top of the lower Minnewanka was encountered at 1,550 (plus 4,540) feet, or about 510 feet higher than it was encountered in Moose Oils No. 1, a gas well about 2 miles southeast of the company's test; and this same zone is about 790 feet higher, structurally, in the McColl-Frontenac test than it is in Moose Oils No. 2, a small oil well about 3 miles southeast.

DEVELOPMENT

The Moose Mountain area was mapped by the Geological Survey of Canada as early as 1905, with the view of locating and describing the numerous coal seams that were known to exist in the general area. A small coal mine was opened about 14 years ago near the mouth of Canyon Creek, from which sufficient coal

was extracted to fire the boilers during drilling operations at the Herron test, a 3,590-foot dry hole about 6 miles southeast of the McColl-Frontenac Oil Company's test. The individual who contracted to move this fuel estimated that about 400 tons of coal were hauled.

In 1933 Moose Oils No. 1, 2 miles southeast of the McColl-Frontenac test, was completed as a gas well, the productive zone being at an estimated depth of 2,610 feet. An oil showing was recorded at 2,200 feet which was not considered of commercial importance, and drilling was suspended at a total depth of 2,834 feet due to mechanical difficulties. The gas from this well is used at Moose Oil No. 2 to heat the buildings and operate a pump and dynamo. A quantity of it was utilized during drilling operations at McColl-Frontenac's Moose Mountain No. 1.

Moose Oils No. 2, drilled in 1937 on Canyon Creek less than a mile east of Moose Oils No. 1, was originally completed at a depth of 1,532 feet. The initial potential is said to have been 8 barrels of oil per day, and this flow was not improved by acidization. The oil zone is thought to be between 1,528 and 1,532 feet, which is in the Devonian, about 1,340 feet below the Banff-Minnewanka contact. A gas zone was encountered at 1,528 feet, and the flow was estimated at 1,500,000 cubic feet per day. The hole was deepened when the oil flow dropped considerably below 8 barrels per day. At 1,675 feet there was a quantity of oil in the hole, and as much as 175 barrels of oil was bailed on one occasion. It was at about this depth that the drilling tools became lodged in the hole; after several attempts failed to remove this iron, the gear was by-passed and the hole was drilled to a total depth of 1,704 feet. When pumping equipment was installed the operators obtained about 625 barrels of oil before the hole was pumped dry. A week later, however, the yield dropped to its present figure of about 8 barrels per day. The gravity of this oil is 47.70° Bé.

A photograph of Moose Oils No. 2 is shown in Figure 6. In this picture also is shown the derrick of the Canadian Royalties Oil Company, located on the Moose Mountain anticline a short distance from Moose Oils No. 2. The drilling of this test had not begun at the time this report was written. The Dome Syndicate is drilling a test with a diamond drill on Elbow River, less than 3 miles south of Moose Oils No. 2. Information received on June 12, 1942, reveals that this hole is drilling in Devonian rocks at a depth of 2,046 feet. The Herron test No. 1, previously referred to, located about 6 miles southeast of McColl-Frontenac's Moose Mountain No. 1, was abandoned at the total depth of 3,590 feet. The bottom of the hole is in limestone belonging to the Rundle formation. Aside from a small flow of gas, nothing of commercial importance was encountered in this well. The test is of interest in that apparently no faults were penetrated on this eastern side of the Moose Mountain anticline.

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VOL. 27, NO 1 (JANUARY, 1943), PP. 51-63, 10 FIGS.

RECENT EXPERIMENTAL AND GEOPHYSICAL EVIDENCE OF MECHANICS OF SALT-DOME FORMATION[1]

L. L. NETTLETON[2]
Pittsburgh, Pennsylvania

ABSTRACT

In 1934 the writer presented a theory of salt-dome formation and illustrated it with a model which indicated: (1) that the motive force causing salt uplift in simple domes is essentially the gravitational force resulting from the fact that the density of the salt is less than that of the surrounding sediments and (2) that both salt and sediments behave essentially as highly viscous fluids. The present paper considers the experimental and theoretical work, largely by others, carried out since that time, which has a bearing on this fluid-mechanical theory.

In 1937 Hubbert considered fundamental dimensional criteria which should be applied to scale models and derived the numerical relations between the physical constants of a model and its prototype in nature which should be fulfilled to give true dynamic similarity. Dobrin in 1941 determined physical constants of a fluid salt-dome model, applied Hubbert's analysis, and established the fact that the model fulfilled the dimensional criteria. By measurement of flow rates and viscosities in a model, he determined the equivalent viscosity for the sediments and arrived at a value which is in reasonable accord with determinations by other means. The experiments by Griggs and the thermodynamic development of the physics of stressed solids by Goranson in recent years have interpreted the physical properties of rock material, in terms of long-time stresses. This work has clarified and evaluated certain fundamental properties such as "strength," "plasticity," *et cetera*, that are directly applicable to the fluid-mechanical postulate of salt-dome formation. Finally, recent extensive geophysical work and drilling around salt domes have revealed the existence, in many places, of rim synclines which are a natural consequence of the fluid-mechanical theory and which were relatively unknown or unrecognized as such at the time of the earlier paper. All of this work seems to confirm the general hypothesis that salt-dome formation is largely a fluid-mechanical process.

Some further model experiments by the writer have been made in an attempt to simulate dome formation where the salt flow is modified by strong layers in the sediments penetrated by the dome. The salt forms thus indicated are shown to be qualitatively similar to reasonable deductions from geophysical and drilling data over a particular dome which probably formed under such circumstances.

In 1934 the writer presented a theory of salt-dome formation[3] which was based on the idea that both the salt and the sediments behave through geologic time essentially as highly viscous fluids. The motive force causing the salt uplift was assumed to arise from purely gravitational forces resulting from the difference in density between the salt and the surrounding sediments. A model illustrating this behavior was shown in which the salt was simulated by a very viscous asphaltic crude oil and the sediments by a heavy syrup. The flowage of the fluids in this model resulting from purely gravitational forces and the difference in density between the two fluids gave rise to forms which were rather closely similar in general outline and proportion to salt-dome forms as known from drilling and as extrapolated to probable depths of the underlying source bed of the salt. From these experiments it seemed reasonable to assume that the model represents, in a qualitative way, the essential process by which salt domes are formed. An important result of the model behavior is the expectation that a peripheral sink or rim syncline should form around salt domes.

The purpose of the present paper is to gather together various geological and

[1] Read before the Association at Denver, Colorado, April 23, 1942. Manuscript received, July 6, 1942.

[2] Gulf Research and Development Company.

[3] L. L. Nettleton, "Fluid Mechanics of Salt Domes," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 18, No. 9 (September 1934), pp. 1175–1204.

geophysical facts which have become available since 1934 which have a bearing on the mechanism of salt-dome formations, to review recent fundamental experiments and theories of deformation of rocks which seem to have a bearing on the processes by which salt domes are formed, and to present some further experiments on a similar model.

MODEL THEORY

The 1934 salt-dome model was almost entirely intuitive in its conception and construction and no attempt was made to determine quantitative relations between the physical properties of the model materials and of the earth materials which they simulated. In 1937 Hubbert published a theory of scale models[4] which outlined the principles by which the numerical relations between the physical constants of a model and the prototype in nature which it represents could be evaluated. Hubbert showed that there are certain very definite restrictions on the physical properties of materials of a model which must be observed if the geologic processes which it represents are to be simulated correctly. As an example, Hubbert applied his analysis to the 1934 salt-dome model and showed that its representation of salt-dome behavior was dimensionally reasonable. This served to justify to a certain extent the intuitive choice of properties of the materials which had been used in making the model.

In 1941, Dobrin[5] carried out a series of experiments in which the principles outlined by Hubbert were applied to a specially designed model which was similar in its general properties to the original 1934 model.

QUANTITATIVE ANALYSIS OF THE FLUID SALT-DOME MODEL

The primary dimensional controls on the physical properties of the salt-dome model which result from Hubbert's analysis are given by the relation $\gamma = \delta\lambda\tau$ where γ is the ratio of the viscosity in the model to that in the geological prototype which it represents, δ is the ratio of densities, λ is the ratio of lengths, and τ is the ratio of times (Fig. 1). If this condition is fulfilled the dome in the model should be geometrically similar to the idealized geologic dome in nature which it represents.

In Dobrin's analysis, the viscosity was taken as the indeterminate or unknown factor to be evaluated from the experiments and the estimated ratios of density, length, and time between the model and its prototype in nature. As indicated in Figure 1, a 12-centimeter height in the model was taken as equivalent to a 20,000-foot height in an actual salt dome, giving the length ratio of 2×10^{-5}. Similarly, the time for a dome to rise in nature was taken as of the order of 100 million years, which gave a ratio of approximately $t/3\times10^{-15}$ where t is the time in seconds required for the model to rise to the height of 12 centimeters. The den-

[4] M. K. Hubbert, "Theory of Scale Models as Applied to the Study of Geologic Structures," *Bull. Geol. Soc. America*, Vol. 48 (1937), pp. 1459–1520.

[5] M. B. Dobrin, "Some Quantitative Experiments on a Salt-Dome Model and Their Geologic Implications," *Amer. Geophys. Union Trans. of 1941*, pp. 528–42.

sity ratios are easily established from the known densities of the fluids and the approximately known densities of salt and sediments.

A series of experiments was carried out in which the viscosity of the fluids in the model was varied (by changing their temperature) through a range of the order of 10,000 and the corresponding rates of dome formation determined. From the numerical data resulting from these experiments, together with the foregoing equation for ratios of dimensions, a value can be calculated for the viscosity of the geological materials which the model simulates. The value so derived (for the viscosity of sediments surrounding the salt) from experiments with asphalt as the light fluid is 1.4×10^{21} poises.

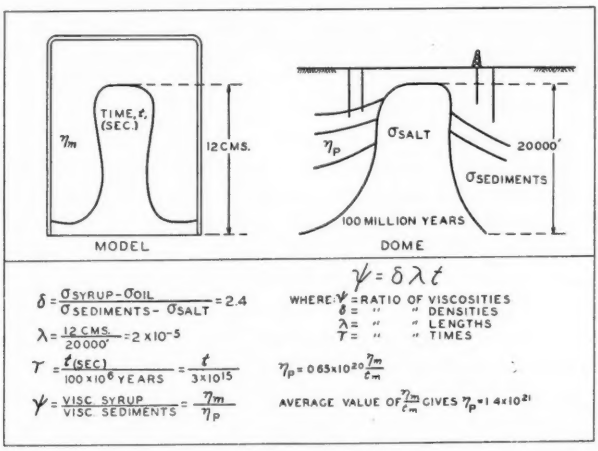
TIME, t, (SEC.)
η_m
12 CMS.
MODEL
σ_{SALT}
η_p
20000'
$\sigma_{SEDIMENTS}$
100 MILLION YEARS
DOME
$\psi = \delta \lambda \tau$
$\delta = \frac{\sigma_{SYRUP} - \sigma_{OIL}}{\sigma_{SEDIMENTS} - \sigma_{SALT}} = 2.4$
$\lambda = \frac{12 \text{ CMS.}}{20000'} = 2 \times 10^{-5}$
$\tau = \frac{t \text{ (SEC)}}{100 \times 10^6 \text{ YEARS}} = \frac{t}{3 \times 10^{15}}$
$\psi = \frac{\text{VISC. SYRUP}}{\text{VISC. SEDIMENTS}} = \frac{\eta_m}{\eta_p}$
WHERE: ψ = RATIO OF VISCOSITIES
δ = " " DENSITIES
λ = " " LENGTHS
τ = " " TIMES
$\eta_p = 0.65 \times 10^{20} \frac{\eta_m}{\ell_m}$
AVERAGE VALUE OF $\frac{\eta_m}{\ell_m}$ GIVES $\eta_p = 1.4 \times 10^{21}$

FIG. 1.—Relations between salt-dome model and its prototype in nature.

It seems impossible to compare this figure with other determinations of a value of viscosity for similar materials under similar circumstances. However, it is of interest that the value is one order of magnitude smaller than that computed by Haskell and Vening-Meinesz for the viscosity of rock materials in the outer mantle of the earth's crust which are involved in isostatic adjustment following the removal of the polar ice cap. A rather questionable value, calculated from a tombstone[6] which had sagged (flowed?) is two orders of magnitude smaller. Although data to give a more definite numerical check with physical properties involved in salt-dome flowage in nature are not available at present, the quantitative work, on the whole, gives reasonable results, and it is felt gives distinct

[6] In a small cemetery near the Gulf Research Laboratory, there are two similar tombstones, each about 100 years old, made of flat, horizontal slabs about 6 feet $\times$ 3 feet $\times$ 3½ inches thick supported by vertical slabs near each end. The stones have sagged, presumably by plastic flow under their own weight, by a little more than ⅛ inch. A value for equivalent viscosity, calculated from these data (by T. A. Elkins of this laboratory), is about 2×10^{19} poises. The stone is a greenish, fine-grained, highly micaceous, silty, thinly bedded sandstone. Its origin is unknown.

support to the reasonableness of the fluid-mechanical hypothesis for salt-dome formation.

Another interesting result of Dobrin's analysis of his experiments was the indication, based on (1) a hydromechanical analysis of the data and (2) an experiment with oil of a much lower viscosity (but with the same syrup) which gave substantially the same rate of rise, that the control on the rate of formation of the model dome and presumably also on the dome in nature depends much more, and in fact very largely, on the viscosity of the surrounding heavy fluid than on that of the lighter fluid rising within it. From this it may be assumed that the conditions for the formation of domes in nature include important control given by the "equivalent viscosity" of the sedimentary material through which the dome rises and that this may be more important than the plastic properties of the salt itself.

FUNDAMENTAL PHYSICAL PROPERTIES OF ROCKS

In recent years extensive experiments have been made on the determination of physical properties of rocks under experimental controls which have tried to simulate conditions under which rock deformations occur in nature. While a number of names in both Europe and America are concerned with this work the most extensive recent experimental work and that which appears most directly pertinent to problems of rock flowage is that by Griggs. Throughout a number of years Griggs[7] has made tests of rocks under stress through long periods of time to determine rock properties which might control their behavior under geologic deformation. In particular he has measured flowage of rocks under high confining pressures and more recently in the presence of solutions[8] to approximate conditions at considerable depths within the earth's crust. In general, Griggs has found[9] that the deformation of rocks can be represented by an expression of the form $S=A+B \log t+Ct$ where S represents the total deformation in time, t, under constant stress. The first term (Fig. 2) represents the ordinary elastic strain corresponding with short-time engineering tests. The second term represents what Griggs calls "elastic flow" which is a deformation at a rate decreasing with time, but which is "elastic" in the sense that the deformation reverses when the stress is relieved. The third term is what Griggs calls "pseudo-viscous" flow and is a non-reversible deformation which is not recovered when the stress is relieved.

It is evident that in terms of an expression of this kind our ordinary concept of "strength" loses its significance as the value obtained depends upon the time during which the test is carried out. The ordinary strength for short-period tests (Fig. 3), which corresponds with the first term only of the foregoing equation,

[7] David Griggs, "Creep of Rocks," *Jour. Geol.*, Vol. 47, No. 3 (April–May, 1939), pp. 225–51.

[8] *Idem*, "Experimental Flow of Rocks under Conditions Favoring Recrystallization," *Bull. Geol. Soc. America*, Vol. 51 (1940), pp. 1001–22.

[9] *Idem*, *Jour. Geol.*, p. 228.

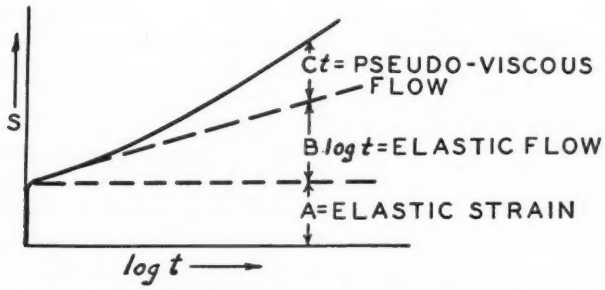

FIG. 2.—Physical meaning of three parts of Griggs-Goranson formula.

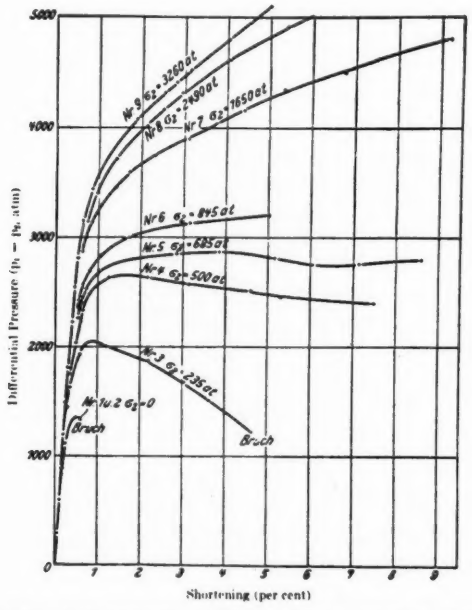
Differential Pressure (p1 − p2, atm)
Shortening (per cent)
Nr 9 σ2 = 3260 at
Nr 8 σ2 = 2490 at
Nr 7 σ2 = 1650 at
Nr 6 σ2 = 845 at
Nr 5 σ2 = 685 at
Nr 4 σ2 = 500 at
Nr 3 σ2 = 235 at
Nr 1u 2 σ2 = 0
Bruch
Bruch

FIG. 3.—Karman's stress-strain curves for marble tested in compression under confining pressure. Values of confining pressure (σ_2) shown for each curve. (From Birch, *op. cit.*, p. 124.)

is increased by high surrounding pressure.[10] However, the flowage as represented by the third term of the equation is materially increased by high surrounding

[10] Francis Birch *et al.* (editors), "Handbook of Physical Constants," *Geol. Soc. America Spec. Paper 36* (January 31, 1942), pp. 124 and 130.

pressure with a corresponding decrease in the equivalent viscosity.[11] Thus it seems probable that the differential stresses which rocks can withstand throughout geological time is *decreased* by burial and consequent high surrounding pressure. This is contrary to speculation as to the behavior of crustal rocks at depth, by Jeffreys for instance,[12] who argues, from experimental results similar to those of Figure 3, that the strength of rocks increases with the depth of burial.

Some recent tests of Griggs[13] have been carried out on rock materials in the presence of solutions and have led to surprising results which are probably of great importance in connection with the mechanism of geologic deformation. It is found that the rate of flowage is enormously increased (and the "strength" correspondingly decreased) in the presence of solvents. For instance, marble in the presence of carbonated water has only 20 per cent of the strength shown in the dry state. The most extensive experiments were made on alabaster in the presence of water. These showed a flow rate many times greater than tests on the same material when dry (Fig. 4). The equivalent viscosity is dependent on

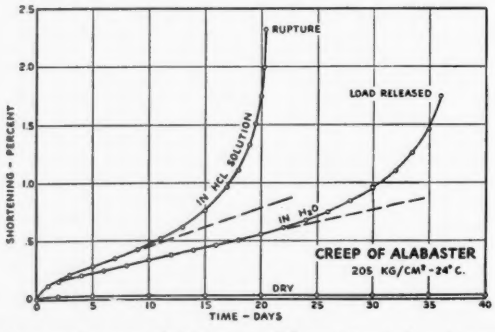

FIG. 4.—Griggs' curves for creep of alabaster in different chemical environments. Specimens were all under same load and at same temperature, but one dry, one in distilled water, and one in diluted HCl. (From Griggs, *Bull. Geol. Soc. America*, Vol. 51 (1940), p. 1012.)

stress but is of the order of 100 times less for tests made in the presence of water than when dry.[14] Furthermore, tests made in the presence of solution and in the presence of a confining pressure of 1,000 atmospheres show that the equivalent viscosity is decreased and is two to six times[15] less than that measured without the

[11] Griggs (*Jour. Geol.*, p. 235) gives the equivalent viscosity of Solenhofen limestone as approximately 2×10^{22} poises for a test under load of 1,400 kg./cm.² at atmospheric pressure. The same material, tested under a load of 5,500 kg./cm.² and under a confining pressure of 10,000 atm. (*ibid.*, p. 245) had an equivalent viscosity of around 1×10^{15} (or 20 million times smaller).

[12] Harold Jeffreys, *The Earth*, p. 128. Cambridge University Press (1924).

[13] David Griggs, *Bull. Geol. Soc. America.*

[14] *Ibid.*, p. 1017.

[15] *Ibid.*, p. 1020.

confining pressure. From these tests it appears justifiable to expect rates of flow for a given differential stress for rocks under high confining pressures and in the presence of solutions which are very much, possibly thousands or even millions of times, greater than might be expected from ordinary engineering tests on the same materials and in the dry state.

Goranson[16,17] has developed a thermodynamic theory of flow in stressed solids which appears applicable to geological processes. The essential basis for Goranson's theory is that solubility is a function of stress. In the application to geologic processes, involving an aggregate of particles under stress and in the presence of a solvent, we might expect stress concentrations at points of contact between individual grains with consequent increase in solubility at these points. This should lead to solution of material from these stressed points, making a super-saturated solvent from which precipitation would occur at unstressed places. This solution at one point and deposition at another constitute a transfer of material which in the aggregate makes up a "flow," giving the material a "viscosity." The analysis of a general system of this type, carried out through thermodynamic considerations of the "activity" and the expressions for the rate of change of solubility with pressure, leads to an expression having the same form as that mentioned above and shown in Figure 2, which Griggs found would explain his observations. Furthermore, this theoretical analysis of the behavior in the presence of a solvent leads to a prediction of the higher rate of flow, that is, lower viscosity, under high confining pressure, than at atmospheric pressure, and the computed ratio of the flow rate under a confining pressure of 1,000 atmospheres to that at one atmosphere was close to that observed.

APPLICATIONS TO SALT-DOME MECHANICS

It is too early to attempt any quantitative applications of the results of Griggs' experiments and Goranson's theory to the mechanics of dome formation. However, the indicated relatively low values of equivalent viscosity under high confining pressures, and especially in the presence of solutions, point to a fluid mechanism of flowage as being entirely reasonable and also point to our intuitive feelings about these properties, based on ordinary experience or engineering tests, as being very grossly in error. Definite data on materials involved in salt-dome formation would be desirable, but it is probable that further experimentation will have to await more settled world conditions. Data on the strength and flowage of salt under confining pressures and in the presence of water would be highly desirable. The only measurement reported[18] is a test on halite, dry, and with no confining pressure, which gives a value for the equivalent viscosity of 2.6×10^{17} poises. In line with the tests on alabaster and marble, it would be ex-

[16] Roy W. Goranson, " 'Flow' in Stressed Solids. An Interpretation," *Bull. Geol. Soc. America*, Vol. 51 (1940), pp. 1923–34.

[17] *Idem.*, "Physics of Stressed Solids," *Jour. Chem. Physics*, Vol. 8, No. 4 (April, 1940), pp. 323–34.

[18] David Griggs, *Jour. Geol.*, p. 241.

pected that a viscosity several orders of magnitude lower than this might be applicable to conditions of high confining pressure and the presence of solutions.

There are two problems in connection with salt flowage which are not solved by elementary considerations of the fluid mechanics of dome formation. These are: (1) the fact that domes ordinarily occur where the salt is under considerable overburden and the implication therefrom that a minimum overburden is required; and (2) the question of what stops the formation of domes and why, once started, they do not all rise to the surface. The first question may possibly have an answer in the indication from Griggs' measurements that the equivalent viscosity decreases with increasing confining pressure. Possibly a pressure corresponding with the order of 10,000 feet of overburden (approximately 700 atmospheres) may be required to reduce the viscosity of salt and sediments to a figure low enough to permit flowage under relatively small differential stresses.

The only new development which at the moment seems applicable to the problem of why domes quit rising is the influence of solutions. It seems generally true that the salt in domes is very dry. The manner in which the water from which it was deposited was so completely removed is not known, but if that removal took place during or after the development of the domes we might possibly have a great increase in the equivalent viscosity and consequent slowing of development of domes resulting from the removal of the water.[19]

GEOPHYSICAL EVIDENCE OF DOME FORMATION

In the years since the fluid mechanical concept of dome formation was first suggested there has been much geophysical work around domes, particularly reflection-seismograph surveys, which has given information on the nature and extent of the sedimentary deformations to considerable depths in the areas immediately adjacent to the salt itself. This is particularly true in the Gulf Coast. Many cases of at least partial, and in some instances fairly complete, rim synclines surrounding domes have been shown by this work. It seems unnecessary to give detailed examples with maps, but a few instances may be mentioned. On the southwestern side of Moss Bluff dome there is a dip toward the dome of nearly 1,000 feet in a few miles just outside the edge of the salt, indicating a strong rim synclinal development in that area.

Figure 5 (modified from an illustration given by Campbell)[20] shows seismograph reflecting horizons near the Hoskins Mound dome which suggest deep faulting that would be a reasonable accompaniment of a rim syncline. Figure 6 (from Gulf Research and Development Company records) shows reflecting horizons (in their off-set positions) on the southerly side of the Allen dome, Brazoria County, Texas. The pronounced dips toward the dome at 8,000–10,000 feet, contrasted with the steep dips away from the dome at shallow depths, again

[19] This suggestion is open to an obvious rebuttal in the fact that salt deposits generally are dry, whether in domes or not.

[20] F. F. Campbell, "Deep Correlation Reflections near Hoskins Mound Salt Dome," *Geophysics*, Vol. 6, No. 3 (July, 1941), pp. 259–63.

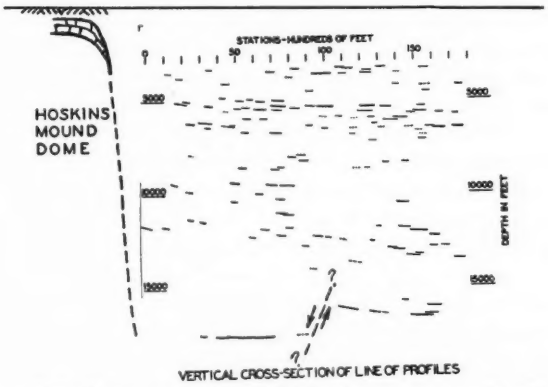

FIG. 5.—Reflections on north side of Hoskins Mound dome (modified slightly from Figure 3 of Campbell, *Geophysics*, Vol. 6, No. 3 (1941), p. 262).

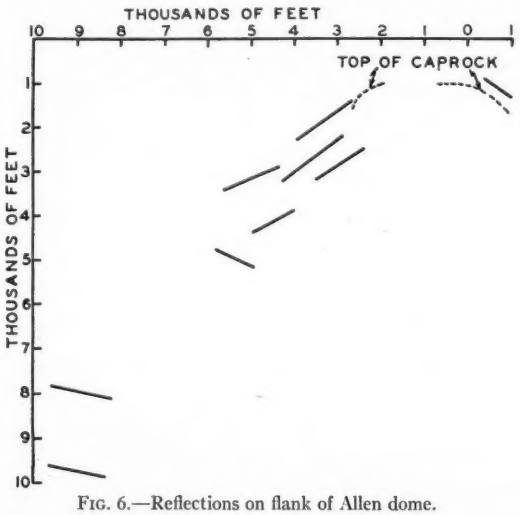

FIG. 6.—Reflections on flank of Allen dome.

strongly suggest a deep rim syncline. Ritz[21] has pointed out that rim synclines may combine to form an interdomal "high" of commercial importance, the Hardin field, Liberty County, Texas, being an example.

EFFECT OF COMPETENT BEDS

In the Gulf Coast the beds through which the salt has penetrated are largely relatively recent sands and shales with only small thicknesses of limestones; therefore, on the whole, the section may be considered as relatively homogeneous

[21] C. H. Ritz, "Geomorphology of Gulf Coast Structures and Its Economic Significance," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 20, No. 11 (November, 1936), pp. 1413–38.

and incompetent, probably incapable of withstanding even moderate stresses for any considerable time. On the other hand, the section through which salt domes have penetrated in northern Louisiana and southern Mississippi contains a series of fairly heavy limestones and anhydrites in the Cretaceous, and it seems quite possible that these relatively competent beds have materially modified the salt flowage. There are some features about the geophysical evidence around these domes which are difficult to explain without resort to dome forms which are quite different from those which would be expected by simple buoyant flowage, such as seems adequate to explain most of the geophysical facts in the Gulf Coast.

As an example, Figure 7 indicates some of the geological and geophysical facts around the Minden dome in northern Louisiana and the deductions which may be made therefrom.

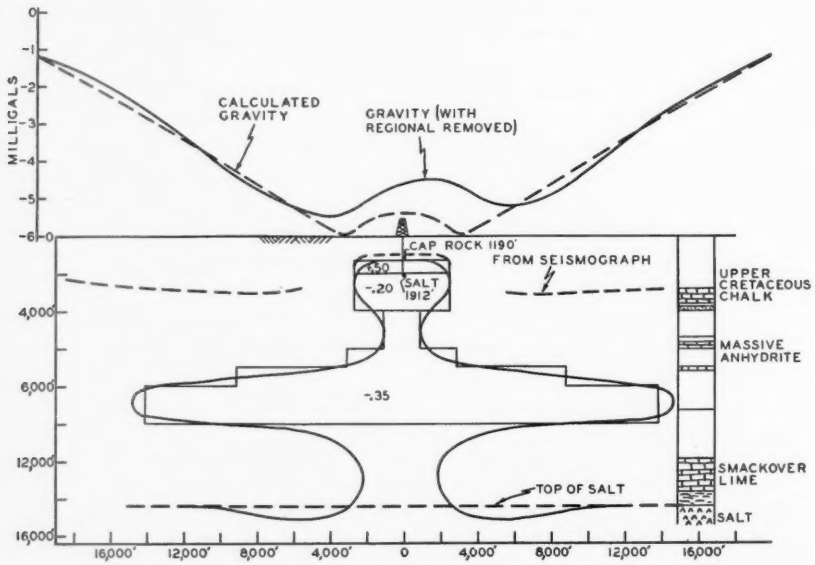

FIG. 7.—Minden dome, Webster Parish, Louisiana, geological and geophysical data, and inferred form of salt. Calculated gravity curve is that given by salt mass with stepped boundaries and density contrasts shown. (Smooth boundary would give substantially same effect.) Wide salt mass is required to give wide gravity curve, if salt mass can not be deeper than normal depth to salt shown.

A test, probably near the center of the dome, shows cap rock at 1,190 feet, salt at 1,912 feet. A torsion-balance survey indicates a broad gravity minimum with a central cap-rock "high". A refraction-seismograph survey indicates a shallow dome with a diameter of about 5,000 feet and a depth to cap of about 1,000 feet. A reflection-seismograph survey on the flanks indicates a horizon at a depth of about 3,500 feet (probably the top of the Cretaceous) having a rim

syncline with a radius of about 7,000 –8,000 feet. The interval between the base of the massive anhydrite and the top of the salt, indicated by a few deep wells in the general area,[22] is about 7,500 feet. Regional subsurface contours indicate that the base of the massive anhydrite near the Minden dome is at a depth of about 7,000 feet. From these figures, we may infer, with some confidence, that the depth to the normal salt at Minden is between 14,000 and 15,000 feet.

Now let us try to devise a dome to fit these facts. The first guess would be that it is a simple cylindrical dome, but when the gravity effect is calculated from such a dome, having its base at a depth of 14,000 feet, the resulting curve is very much narrower than that observed and it is evident that the width of the gravity expression must come from the width rather than the depth of the salt mass if this salt mass is less than 14,000 feet deep. This indicates that there is a more or less disc-like salt mass. The presumption is that the salt rose to possibly a little below the massive anhydrite which was strong enough to resist the salt movement and to cause the salt to flow out laterally rather than to continue its rise. At some later time, assumably Tertiary, the dome finally broke through so that a narrow and possibly much overhung central part rose to give the cap rock shown by the test and the close-in rim syncline as indicated by the reflection-seismograph survey. Some experiments[23] in an attempt to simulate this behavior are here described.

The model used in these experiments is the same as used by Dobrin. Figure 8[24] shows the behavior of this simple, cylindrical model. In Figure 9 the model is modified by the insertion of a rigid steel plate with a central hole of about one-third the diameter of the jar. In the third test (Fig. 10) the diaphragm is of similar dimensions and opening, but is made of soft rubber. These experiments have been made with the idea that the diaphragm may, in a crude way, simulate the obstruction to salt flow which may be caused by an overlying bed of very strong rocks.

With the rigid diaphragm the constriction caused by the plate is severe because, as any of the oil moves up into the space above, a corresponding volume of syrup must be displaced downward through the same opening. This tends to cause a rather sharp cut-off of the oil (salt) supply immediately above the plate, resulting in a slender and quickly pinched off or mushroomed dome (Fig. 9). The rigid steel plate is certainly much too strong to be an analog of any actual sedimentary layer. However, the situation may be somewhat closer to conditions in nature than is at first apparent, as the break-through of the rising oil into the

[22] At Lisbon (25 miles northeast) the Union Producing Company's Meadows test No. 1A gives this interval as 7,857 feet; at East Haynesville (25 miles north) the Hunt Oil Company's M. B. Mitchiner test No. 1 gives 7,107 feet: at Pine Island (40 miles west-northwest) R. W. Norton's Payne test No. 1 gives 7,458 feet.

[23] An experiment of this type was suggested to the writer by Paul Weaver.

[24] Figures 8, 9, and 10 are from selected frames of the 16 mm. moving-picture film which was shown when this paper was given at the Denver meeting. The time spacing of the pictures is uniform for each group.

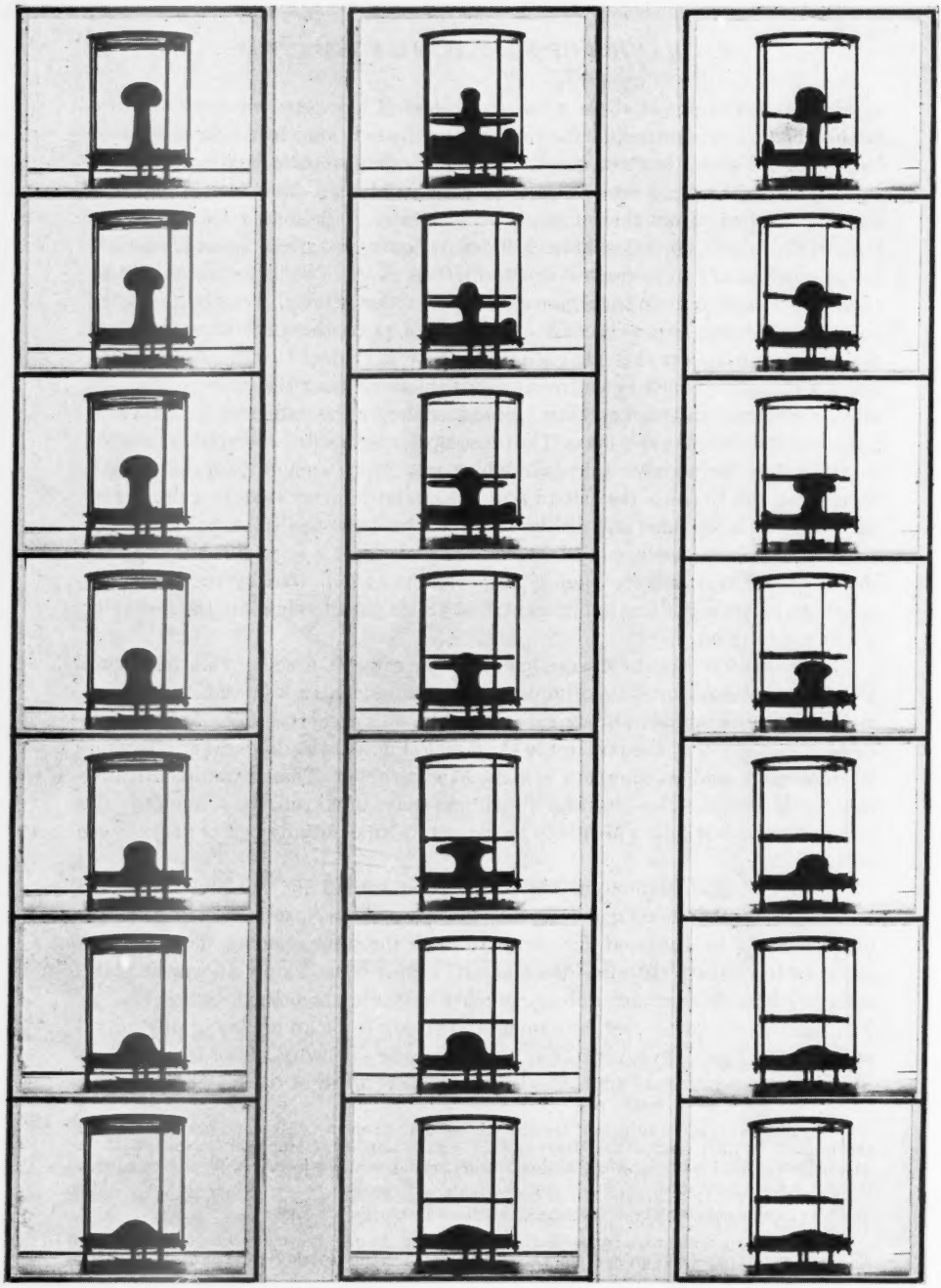

FIG. 8 (left).—Formation of model dome with no obstruction (simulating homogeneous overburden).

FIG. 9 (middle).—Formation of dome under and through rigid steel plate (control opening in plate is $\frac{1}{3}$ diameter of jar) simulating dome piercing very competent beds.

FIG. 10 (right).—Formation of dome under and through rubber diaphragm (same size opening as in Figure 9) simulating dome piercing less competent beds.

upper part might be considered to correspond with the rupture of an overlying competent bed by rising salt.

In the test with the rubber diaphragm (Fig. 10) the same general forms are developed but not to such an extreme degree.

The rough correspondence of the forms of this model, particularly those of Figure 9, with those derived from calculation from the observed geophysical effects around Minden (Fig. 7) suggest rather strongly that a mechanism somewhat similar to that indicated by the model is actually followed in the formation of domes in areas overlain by highly competent beds.

The contortion of sediments and salt which would be required if conditions similar to those of Figures 7, 9, and 10 actually exist, may seem unreasonable to many. However, our notions of the physical properties of rocks as they apply to deformation under conditions of geologic structure formation are still mainly qualitative. For instance, may not conditions similar to those controlling salt domes apply to the formation of diatomite structures, such as Lost Hills and Belridge in California? The density contrast is certainly there (as shown by strong gravity minima over the structures) and the surrounding rocks are rather similar to those of the Gulf Coast. Intuitively we feel that the siliceous diatomite would not flow like salt, but our feeling may be wrong. The work of Griggs and Goranson has made a start toward supplying numbers which can be applied to questions such as this and to the physics of geologic deformation. It seems certain that more work in this direction and a greater appreciation and use of such work by structural geologists, together with a proper application of dimensional criteria by the geological model builders, will lead to very great advances in knowledge of the fundamentals of structural processes.

In conclusion, the writer wishes to express his appreciation to his colleagues of the geological and geophysical staffs of the Gulf Companies, too numerous to list individually, who have contributed to this material, more or less unwittingly, during discussions covering a period of many years, and to P. D. Foote and E. A. Eckhardt for permission to publish this paper.

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TECHNIQUE OF TESTING LARGE CORES OF OIL SANDS[1]

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ABSTRACT

Testing samples of oil sands for determining productivity of oil wells and estimating reserves has been described and discussed by many authors. Most articles suggest the use of small 2½-centimeter cubes. Since texture, porosity, and permeability of some rocks, particularly limestone, vary greatly in short distances, very large numbers of small samples are needed to determine even an approximate average permeability, porosity, and fluid content of large slices of rock samples. A discussion is presented of the feasibility and advantages of using large core samples and the effect of several factors such as minute quantities of connate water, presence of traces of emulsions, and presence of certain colloids, on results of fluid-flow measurements in large core samples. The paper includes tables showing the porosity, permeability, gravity, and fluid content of several oil-bearing formations in Texas.

INTRODUCTION

Advantages of using large cores.—The testing of oil sand for estimating oil reserves and determining productivity of oil wells is a major item in petroleum engineering work. Methods have been described and discussed by many writers (1–38).[3] Most engineers use only small chunks of the oil sand; generally they recommend cubes or cylinders about 2½ centimeters in size (2). If all oil sands were of uniform texture, porosity, and permeability, results obtained from a small cube would be representative of the sand as a whole. Most oil formations, however, especially those obtained from limestone reservoirs, are very irregular in porosity and permeability, varying all the way from 6 to 25 per cent in porosity and zero to 3 darcys or more in permeability even where the samples are obtained only a few feet apart. Accordingly, in order to obtain the average permeability or porosity of a reservoir, large numbers of samples need to be tested. If, on the other hand, a core sample that is 3 inches in length and 2½ inches in diameter is employed, then fewer tests are needed. In fact, on the basis of volume, 4 tests of these large cores are roughly equivalent to 61 tests of the small cubes. Thus, much time and tedious work may be saved, if the large cores can be handled properly. It is easier to prepare and easier to manipulate a large core since slices of cores obtained from the well after cleaning can be used directly with minimum preparation. On the other hand, large cores are somewhat more difficult to extract thoroughly, require more solvent, more expensive equipment, and somewhat different technique from the small fragments. The following pages describe and illustrate the technique and methods employed in a series of experiments designed to determine the feasibility of using comparatively large cores of oil sands in place of the small cubes.

Common tests for oil sands.—Many tests for oil sands have been devised

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[3] Numbers in parentheses refer to references at the end of the paper.

and their descriptions published (1–38). The commonest and most practicable of these tests are: (1) fluid content, that is, percentage of oil and percentage of water, (2) porosity, (3) permeability, (4) specific gravity. The specific-gravity test is used in calculating the porosity of the sand and the others in obtaining factors for evaluating the productivity and performance of the oil reservoir. These tests applied to large cores of 200 cubic centimeters or more in size will be described in the following paragraphs.

METHOD OF PREPARING LARGE CORE

Sections of rock cores obtained from oil-well core drills are used. A core $2\frac{1}{2}$ to 3 inches in diameter is perhaps most convenient. This is sliced in lengths of about 3 inches with a diamond-impregnated circular or hack saw held in a miter box. The slice is then placed beneath a drill and a $\frac{3}{8}$–$\frac{1}{2}$-inch hole drilled vertically through the center. The same fluid which will be used later for the flow measurements should be applied to the bit to keep it cool and to remove the cuttings. During these operations the core is held in clamps between strips of clean absorbent paper. If the core is limestone and if water has been used, it is then dipped in a dilute solution of HCl, brushed with a clean brush, rinsed in distilled water, and then dried at 100°C., weighed and dried again until all the water is removed. If the core is sandstone and oil has been used, the treatment with dilute acid is omitted, but it should be brushed thoroughly with a clean brush and all foreign material removed. The core is placed between Neoprene gaskets in a core holder (25, Fig. 5) and is ready for the tests.

DETERMINATION OF FLUID CONTENT

Method of extraction.—The fluid content of the core is determined by a pressure-extraction method. The apparatus used is illustrated in Figure 1. The core is weighed accurately on a sensitive balance and placed in the cylinder, *A*. A solvent, pentane or acetylene tetrachloride, is then added from the bottle, *B*, through the lubricator, *C*, and allowed to flow under pressure to the center of the core, through the core, and out into a receiver, *R*. Pressure is applied to the solvent in the lubricator from a compressed-air source through a regulator. From the receiver the solvent is pumped by a small rotary pump, *P*, back into the container, *B*. If the solvent is deeply colored with oil extracted from the core, it is run from the container to a still (not shown in the diagram) and recovered for use again. If it is colorless or only slightly stained, it is run back into the lubricator, *C*, and through the core again. Circulation of the solvent through the sample is kept up until the solvent comes through colorless or nearly so. The length of time required depends on the permeability of the core and the amount of pressure used to flow the fluid. It often requires 48 hours and, therefore, if a large number of cores are to be tested, a bank of 10 or more extractors should be set up and a corresponding number of stills employed to recover the solvent. However, unless it is desired to know the oil content of the large cores, the used

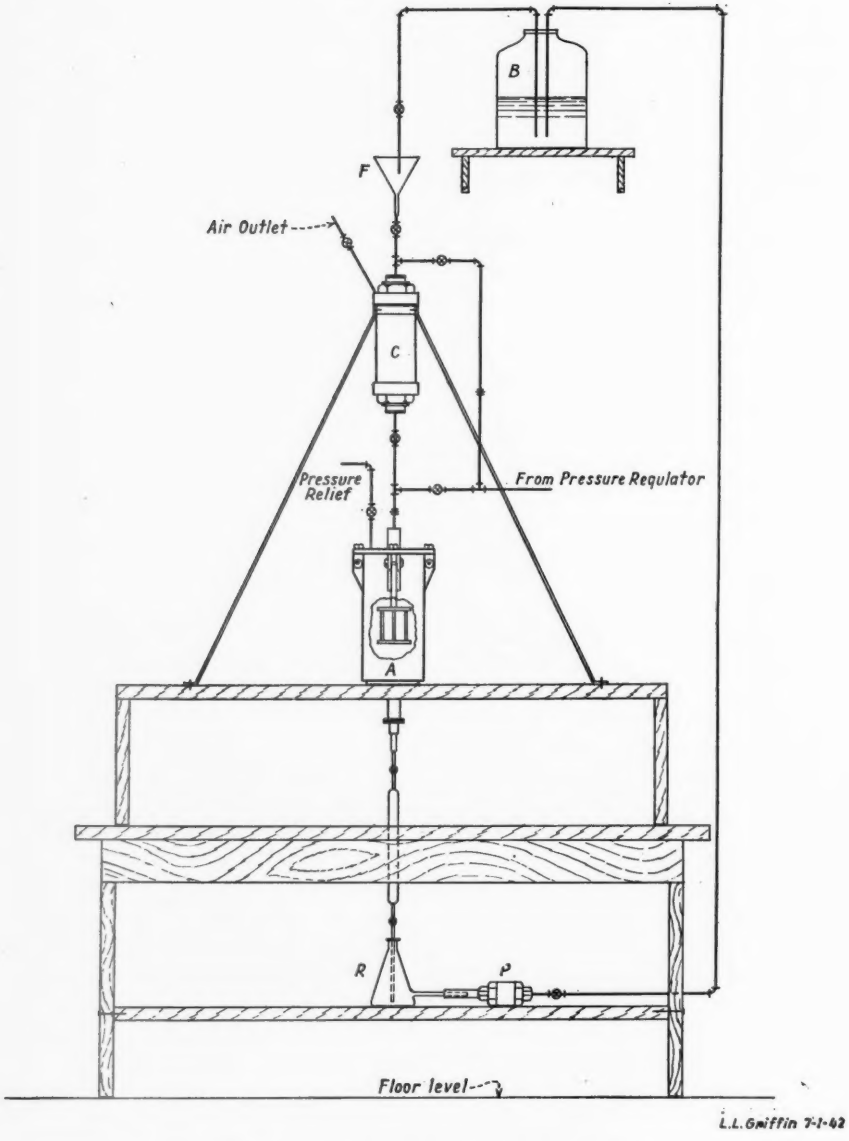

FIG. 1.—Apparatus used in extracting oil from cores.

solvent can be piped to a single container and recovered in a single large still.

Determining volume of fluid.—The bulk of fluid left in the still after the solvent has been distilled off is weighed, and the specific gravity of the fluid determined with a Westphal balance (13) and the volume of the fluid calculated. If water is present, the water content of the fluid may be determined in a Marsh flask (3, 7, 13, 31). Very little water, however, is removed by pressure extraction in most cases.

Table I shows the results[4] of typical extractions made by this method compared with those made in a Soxhlet extractor from an adjacent slice of the same core.

TABLE I

Formation	*Pressure Extraction*		*Soxhlet Extraction*	
	Sample Number	*Percentage Asphaltic Oil Determined*	*Sample Number*	*Percentage Asphaltic Oil Determined*
Trinity sand, St. Joe, Montague County, Texas	1	10.1	2	10.7
	4	10.0	3	10.4
	5	8.6	7	10.5
	6	11.5	9	12.3
	8	12.0	10	12.5
Anacacho limestone, Uvalde County, Texas	4	10.6	3	11.30
	6	11.0	5	11.70
	7	9.7	8	10.30
	9	8.4	10	10.70
	12	10.40	11	10.40

Discussion of results of fluid determination.—The results are not exactly comparable because obviously the same samples could not be used for the same test. For pressure extraction a large cylindrical sample 2 inches in diameter and 3 inches long was used. For Soxhlet extraction (8, 12, 22, 29) a small chunk 1 inch by 1 inch by 1 inch taken from the same rock was used. The results obtained by the pressure-extraction method probably give a lower percentage of oil than by the usual Sohxlet method. This is because it is probably impossible to get all the oil out of a large core by flowing cool solvents through it. In fact, fine-grained asphaltic samples extracted for two days will still yield some discoloration of the solvent. Therefore, the process, to be absolutely complete, may be long and require much solvent distillation. Furthermore, in high-gravity oils, it has been noted that there is probably a loss of some oil during the evaporation of the solvent unless special stills are used. This latter error, however, applies equally to the common Soxhlet extraction methods and these inevitable losses may not be very serious. It is probably true that only the oil which will flow through the open free passageways in a sand is recoverable and that oil not reached in cores by solvents after 24 hours of washing by the above method should be regarded as

[4] Determined by William Terry.

unrecoverable. A check of this conclusion was made by drying and weighing an extracted core on a sensitive balance, then replacing the core in the extraction apparatus and flowing solvent through for another 10 hours, then drying, and weighing again. During the second procedure a slight discoloration of the solvent was still observed, but the change in weight of the sample after drying to constant weight again was insignificant. Recently Taliaferro and Heithecker (32, p. 62) have devised a special Soxhlet extractor for large core samples, which might be effectively used in place of the pressure extractor. However, the extraction is

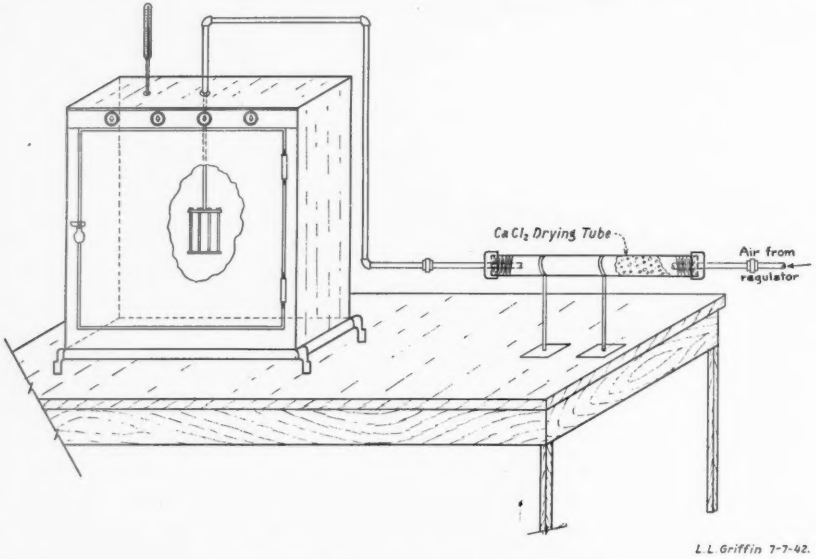

FIG. 2.—Apparatus used in drying cores.

thought to be more complete, when the solvent is forced through the pores of the sample.

Method of removing solvent and determining water content.—After the oil has been extracted, the cores are removed from the cylinders, heated to 40°C., slightly above the boiling point of pentane in the dehydrating oven (Fig. 2.) Air is passed through the core, while it is in the oven, for about 30 minutes or until all odor of the pentane is removed from the oven. The core is then removed from the oven and weighed carefully on an analytical balance. It is then placed in the oven again and heated to above 100°C. for several hours, and hot dry air is passed through the core under a pressure of about 50 pounds per square inch (Fig. 2). It is then removed from the oven and weighed, then heated again until constant weight is obtained. The loss in weight represents the moisture content removed by the dehydration process.

Table II shows the results of moisture determination in Glen Rose limestone from Bell County.

TABLE II

Sample No.	*Time (Hours)*	*Weight of Sample (Grams)*			*Volume of Core (Cc.)**	*Water (Per Cent)*	*Porosity (Per Cent)*
		Wet	*Dry*	*Loss*			
13	32	249.51	226.17	23.34	105.5	9.32	22.12
3	19	362.84	334.84	28.00	150.5	7.71	18.80
2	26	360.01	335.91	24.10	146.4	6.70	20.01
16	36	365.22	327.16	29.04	147.5	8.15	19.91
9	24	351.84	322.78	29.00	149.0	8.24	20.06

* Determined by a special type of picnometer described in this paper (Fig. 8).

No opportunity has occurred to check the results of the moisture determinations against the retort method described by Hill (15) and others (16, 24). An attempt was made to wash out the water by flowing alcohol through the cores at room temperatures and then determining the water by the critical-solution temperature method described by Botset (8) and Taylor (33). Results were much lower than the loss-in-weight method, indicating that interstitial water can not be entirely washed out of the interspaces in a sand without prolonged heating.

DETERMINATION OF PERMEABILITY

Selection of flow fluid.—If it is not desired to measure the oil content of the cores and if the reservoir fluid does not precipitate paraffin, the extraction process need not be carried out, and much time can be saved by mixing up some of the reservoir oil with light hydrocarbon ingredients to match approximately the viscosity of the reservoir fluid and use this mixture as a fluid medium for the permeability measurements. If the cores have been cleaned of oil and other fluids by the extraction process, kerosene is selected generally as the fluid for measuring the permeability because of its stability, cheapness, and availability.

Description of apparatus.—The permeability is determined in a multiple radial-permeability apparatus (Fig. 3). The core holders, *C*, are inserted into the cylinders and the cylinder covers clamped down (25, Figs. 4, 5). Neoprene gaskets are used on the covers to prevent any leakage. Fluid is then allowed to run into the cylinders from the fluid reservoir, *B* (Fig. 3), through the funnel, *F*, until the core holders are immersed beneath at least 3 inches of fluid; the height of the fluid is indicated on the fluid manometer, M_2. The valves leading to the outside of the cylinders are then closed and the pressure turned on through the regulator, *E*. The gauge valve is then opened, the pressure allowed to settle to a constant predetermined amount as indicated by the gauge, *G*, or mercury manometers, *M*, and the valves at the base of the cylinders opened. Fluid is allowed to flow through the cores into the graduated receivers, R^1, R^2, R^3, and R^4, passes out at the lower end of the receiver into the cylinder, *T*, and is pumped by means of a small centrifugal

pump, P, up into the reservoir, B. From the reservoir, it is allowed to flow by gravity into the funnel, F, from which it is filtered and regularly lubricated into the core cylinders by manipulating the valves, V. The entire apparatus except the mercury manometer, M^1, is constructed of brass. After the fluid has circulated through the cores for 1 hour, the graduated flow receivers, R^1, R^2, R^3, and R^4, are closed at the bottom and the amount of flow measured by means of stop watches.

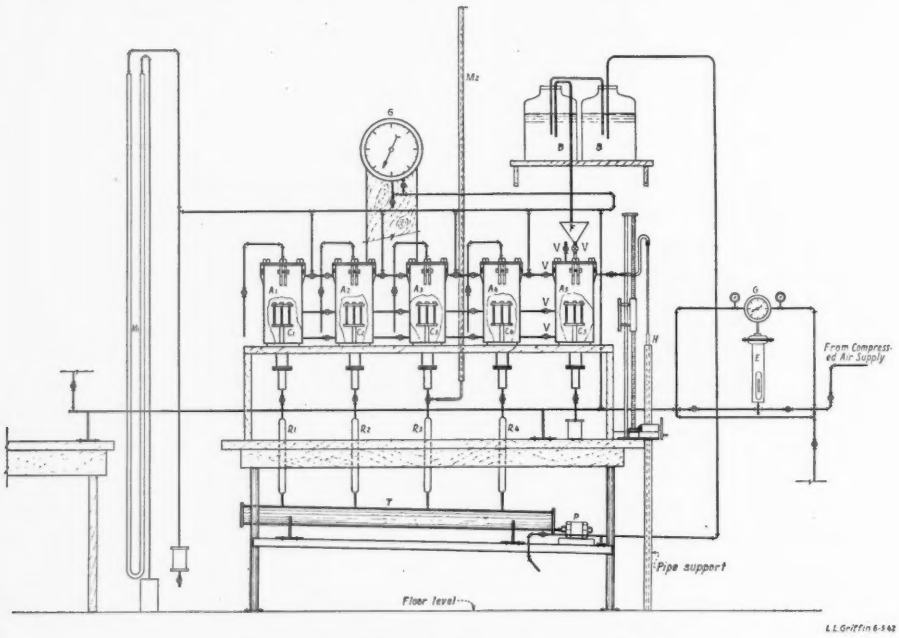

FIG. 3.—Apparatus used in measuring permeability.

The measurements are repeated until constant results are obtained. For very permeable cores, it is best to use low pressures and rates of flow in order to avoid any danger of turbulence.

Methods of maintaining uniform pressures.—Maintaining uniform pressures on the fluid during the flow measurements is most important. This may be accomplished accurately in the following ways.

1. If the core is very permeable and low pressures of $\frac{1}{2}$ to 3 pounds only are desired, an adjustable constant-level head attachment (Fig. 4) is connected to the tops of the cylinders, and the manometer and gauge valves (Fig. 3) are tightly closed. The attachment consists of a copper tank (Fig. 4) mounted on a brass rod and connected with the pressure cylinders by means of a Neoprene hose. Fluid from the receiving cylinder, T, of the permeability apparatus (Fig. 3)

is pumped by the small rotary pump, *P*, to the tank through the Neoprene hose (Fig. 4), overflows through the tube leading to the receiver, and is returned to the cylinder through two Neoprene tubes. As long as the pump, *P* (Fig. 3), is kept running, the head of the fluid in the copper tank (Fig. 4), and consequently the pressure in the cylinder, will remain constant. The hydrostatic head can be changed at will by raising or lowering the copper tank on the rod. The

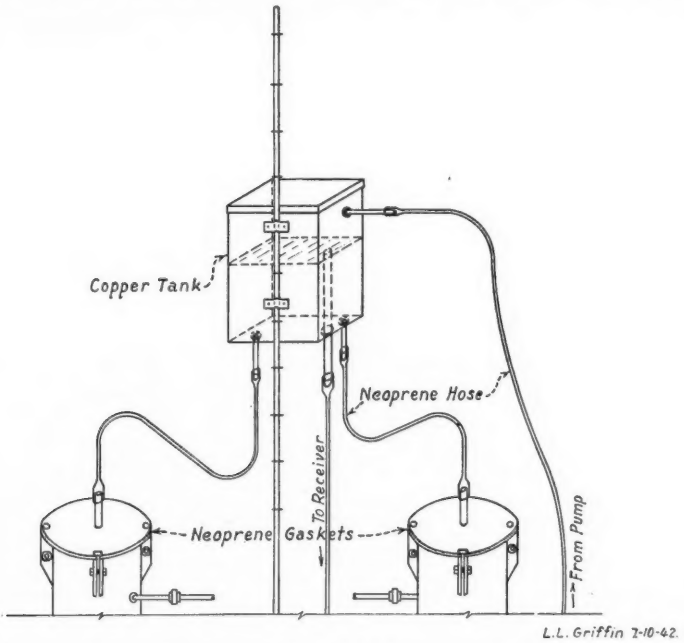

FIG. 4.—Apparatus used in maintaining constant liquid head.

head of fluid, and consequently the pressure, are recorded on the manometer (M^2, Fig. 3). The pressure in atmospheres is calculated or read conveniently from a chart (Fig. 5).

2. If the core is moderately permeable and pressures between 3 and 10 pounds are desired, then the constant fluid-level box is detached and a mercury relief valve, *H* (Fig. 3), is attached to the manometer manifold. The relief valve consists of a $\frac{1}{2}$-inch tube about 6 feet long equipped with an expansion chamber 1 foot below its top set in a supporting pipe. The tube is filled with mercury to a depth of $3\frac{1}{2}$ feet. Then a small capillary glass tube is extended down inside the mercury-filled tube, raising the level of the mercury in the tube about 1 foot. The top of the inner tube is supported by a clamp attached to a vertical screw elevator, *E*, in such a way that the height of the inner tube can be easily adjusted by raising

or lowering the elevator on the vertical screws. The level of the fluid in the cylinders, A, is then set to a point about 3 inches above the top of the cores and air pressure maintained on top of the fluid of about 5.1 pounds by means of the regulator, E (Fig. 3). Then the inner tube is lowered into the mercury column until air will just bubble through when the pressure gauge stands exactly at 5 pounds. As long as the rod remains at this constant level and excess air continues to bubble through, pressure in the cylinders will remain constant.

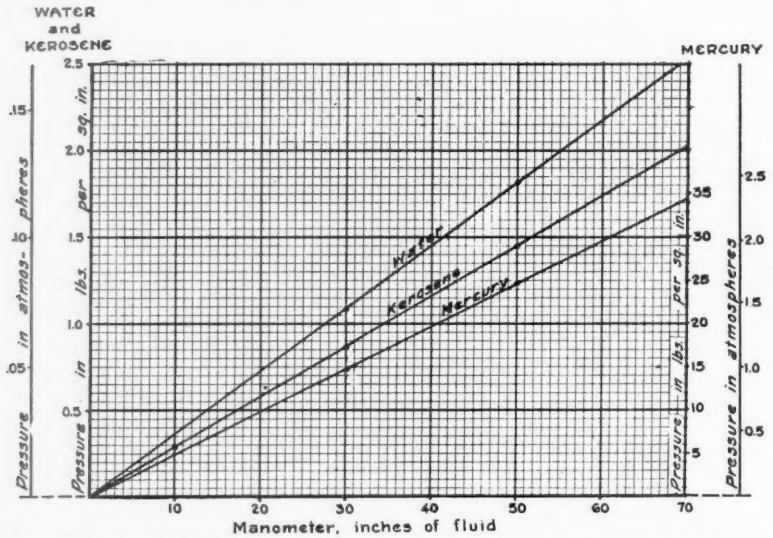

Fig. 5.—Chart showing pressure in atmospheres for different heads of water, kerosene, and mercury.

3. If the permeability of the core is low, and high pressures are desired, it has been found best practice to set the pressure in the supply tank slightly above the desired pressure, then adjust the regulator, E, to the desired pressure. Good regulators operating on pressures above 15 pounds per square inch should maintain pressures within 1/50 of a pound.

Calculation of results.—The permeability (K) is calculated by the formula for inward radial flow (2, 36):

$$K = \frac{Q\mu \log_e \frac{r_e}{r_w}}{2\pi l(p_e - p_w)}.$$

Where Q = rate of flow in cc. per second, μ = viscosity in centipoises, r_e = radius of the core measured from the center of the central hole in cm., r_w = radius of the central hole in cm.; t = the axial thickness of the sample in cm.; and $(p_e - p_w)$ = dif-

ferential pressure in atmospheres. The viscosity of the liquid used in the cylinders is best measured with a calibrated modified Ostwald pipette (9, 10) manipulated in a constant temperature bath. The method is rapid and simple; and if reservoir fluids are used, viscosities should be checked at the end of each permeability measurement.

Tables III and IV show typical results with cores of widely different lithology and permeability.

TABLE III

Formation	*Locality*	*Depth (Feet)*	*Fluid Used*	*Radial Permeability (Millidarcys)*	*Determined by*
Glen Rose limestone	U. S. Army core test, Maxdale, Bell Co., Texas	18.5	Water	0.398	Plummer & Merkt
Do.	Do.	20.5	Do.	2.20	Do.
Do.	Do.	28.5	Do.	0.828	Do.
Do.	Do.	30.5	Do.	0.340	Do.
Do.	Do.	41	Do.	0.226	Do.
Do.	Do.	42	Do.	8.15	Do.
Do.	Do.	43	Do.	0.417	Do.
Do.	Do.	47	Do.	1.324	Do.
Walnut oölite	Cedar Park quarry, Travis County	Surface	Kerosene	2.22	Plummer & Tapp
Do.	Do.	Do.	Do.	1.40	Do.
Do.	Do.	Do.	Crude oil	2.5	Plummer & Livingston
Do.	Do.	Do.	Do.	2.0	Do.
Do.	Do.	Do.	Do.	3.0	Do.
Glen Rose limestone	Oak Hill, Travis County	Do.	Do.	0.700	Do.
Lueders limestone	Lueders, Jones County	Do.	Do.	0.04	Do.
Queen City sand (unconsolidated)	Bastrop County	Do.	Kerosene	2,250	Do.
Do.	Do.	Do.	Crude oil	3,500	Do.
Do.	Do.	Do.	Do.	1,200	Do.
Do.	Do.	Do.	Do.	700	Do.
Do.	Do.	Do.	Do.	300	Do.
Do.	Do.	Do.	Do.	2,800	Do.
Do.	Do.	Do.	Do.	2,800	Do.
Travis Peak sand (consolidated)	U. S. Army water well near Belton, Bell County	720	Kerosene	1.024	Plummer & Tapp
Do.	Do.	731	Do.	0.991	Do.
Do.	Do.	732	Do.	0.978	Do.

Discussion of results.—It is interesting to compare those permeability determinations made by flowing fluids through large cores with the common laboratory method (2, 12, 14) of flowing gas through small chunks. Small chunks, 2 cm. cube were cut out of each large core after the radial-permeability measurements were completed, and these chunks were tested in the permeability apparatus designed by Fancher, Lewis, and Barnes (14), using the standard method (2). A comparison of the results of the two methods is given in Table IV. The results, of course, are not subject to direct comparison, since obviously the small chunks will not have exactly the same pore characteristics as a core many times larger. In general

the linear measurements are larger than the radial ones. The results, as would be expected, however, are closer for sandstone samples than for the limestone samples having pore spaces of much more irregular sizes.

Fluid under pressure flows through all the connected pores of a large core sample. In limestone, the largest percentage of the fluid passes through the largest channels, which may be comparatively few in number and represent a small volume of the pore space of the entire core. When a small chunk is cut out, it is likely to contain one or more of the larger passageways which might not penetrate through a piece of large limestone; hence, larger permeabilities result. Any factor

TABLE IV

Formation	*Location*	*Depth (Feet)*	*Radial Permeability (Millidarcys)*	*Linear Permeability (Millidarcys)*	*Determined by*
Glen Rose limestone	U. S. Army core tests, Maxdale District, Bell Co.	18.5	0.397	2.17	Plummer & Merkt
Do.	Do.	28.5	0.826	2.91	Do.
Do.	Do.	41	2.27	6.97	Do.
Do.	Do.	42	8.15	8.23	Do.
Do.	Do.	43	0.411	2.50	Do.
Queen City sand (consolidated)	Bastrop County	Surface	183.0	110	Plummer & Woodward
Graford sand (consolidated)	U. S. Army core test, Possum Kingdom dam site, Palo Pinto County	30	13.7	13.9	Do.
Do.	Do.	50	110.0	166	Do.
Paluxy sand	Parker County	Surface	518.0	605	Do.

that tends to clog or modify in any way these larger passageways will affect markedly the rate of flow. The common factors that affect flow other than pressure, size of pores, size of cores, and viscosity of the oil are: (1) presence of water in the channels, (2) presence of foreign matter, drilling mud, dirt, grease, or asphalt, (3) formation of emulsions in the core, (4) swelling or physical changes in the cementing material in the core, (5) rearrangement of sand grains and particles, and (6) presence of bacteria, or other organic organisms in the fluid. Most of these difficulties can be overcome by thorough cleaning of the core by the methods described above and using freshly distilled and filtered fluids. The cleaning process, however, as well as the routine processes (2) recommended for the preparation of samples when small chunks are used in place of large cores undoubtedly changes the physico-chemical character of the interior of the reservoir rock. Most reservoir rocks contain from 10 to 30 per cent water with the oil. Water has a definite effect on the permeability (19, 23, 35). The larger the amount of water and the smaller the pore spaces, the greater the effect. In order to test the effectiveness of a little water on the permeability of typical cores, large cores were thoroughly cleaned, extracted, and dehydrated, then saturated with kerosene

and the permeability measured. Next, a small amount of water (about 20 per cent of the available fluid space) was added to the same core, and the permeability

TABLE V

Formation and Location	*Permeability*		
	Dry (Millidarcys)	*After Introducing Water into Interspaces (Millidarcys)*	*Decrease (Per Cent)*
Walnut oölite, Cedar Park, Travis County	2.22	0.905 (About 15 per cent water introduced)	56.7
Travis Peak sandstone, (consolidated), Bell County	1.024	0.453 (About 30 per cent water introduced)	44.24
Queen City sand (unconsolidated), Bastrop County	1,130.0	717.0 (About 18.9 per cent water introduced)	40

measured again. At first a very little water came through the cores with the kerosene but after a few minutes no more water appeared and the permeability became constant. The results of several tests on cores are shown in Table V and Figures 6 and 7.

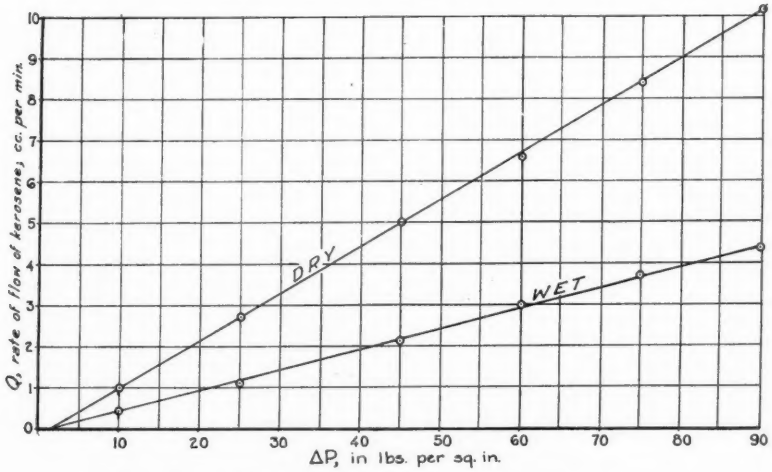

FIG. 6.—Graph showing effect of water on permeability measurements on Walnut limestone, Core No. 1.

It is apparent from these results that addition of small amounts of water decreases the permeability of oil sands by at least 40–50 per cent. This effect is due to the interfacial tension between water and oil in capillary spaces. This effect

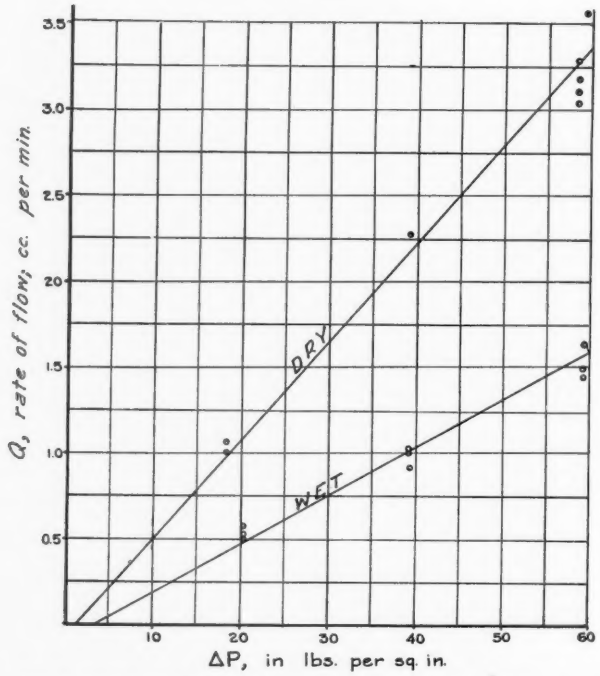

FIG. 7.—Graph showing effect of water on permeability measurements on consolidated Travis Peak sandstone, Core No. 732.

has been investigated by Leverett (19) who concluded that relative permeability is a function of water saturation and a dimensionless number N/PD, which equals

TABLE VI

Sample No.	*Fluid*	*Locality*	*Interfacial Tension (Dynes)*	*Temperature (Degrees F.)*	*Absolute Viscosity of Oil at 100°C. (Centipoises)*
1	Kerosene	Gulf Refining Co., Austin, Travis County	38.3[a]	77	2.01[a]
34	Crude oil	Echo field, Coleman County	34.3[b]	70	2.91[b]
25	Crude oil	East Texas field, Rusk County	19.7[b]	70	4.54[b]
6	Crude oil	Salt Flat field, Caldwell County	23.0[b]	70	5.65[b]

[a] Merkt and Tapp.
[b] Livingston.

TABLE VII

Core Number	Formation	Fluid Used	Viscosity at 70°F. (Centipoises)	Permeability, Dry Core (Darcys)	Core Wet with More than 50 Per Cent Water			Core Wet with More than 50 Per Cent Water Plus Surface-Active Chemical		
					Effective Permeability of Oil	Fluid Yield (Per Cent)		Effective Permeability of Oil	Fluid Yield (Per Cent)	
						Oil	Water		Oil	Water
	1	2	3	4	5	6	7	8	9	10
1	Queen City sand (unconsolidated)	Kerosene	2.3	3.1	0.012	2	98	0.279[S]	95	5
2	Do.	Do.	2.3	2.94	0.0	0	100	0.056[S]	76.51	23.49
3	Do.	Crude oil	3.6	2.86	0.055	20	80	0.045[I]	50	50
4	Do.	Do.	3.6	3	1.91	20	20	1.08[I]	20	80
5	Do.	Do.	3.6	2.8	0.225	40	60	0.160[A]	60	40
6	Do.	Do.	3.6	2.8	0.282	47	53	0.799[A]	83	17
7	Glen Rose oölite	Do.	3.2	0.002	0.00039	96.87	3.13	—	—	—
8	Walnut oölite	Do.	3.2	0.0025	0.0002	99	1	—	—	—
9	Do.	Do.	3.2	0.002	0.000025	9.4	90.6	0.00077[A]	97.72	2.78
10	Leuders limestone	Kerosene	2.3	0.004	0.00044	1.42	98.58	0.0002[A]	50	50

S = Sodium oleate.
I = Igepon.
A = Aerosol.

the product of displacement pressure and the length of the element considered divided by the product of the pressure differential and the average pore diameter. Since displacement pressure is a ratio of the interfacial tension to the average pore radius, this expression according to Livingston (23) can be reduced to IN/PD^2, where I is the interfacial tension. Table VI shows interfacial tensions between water and the oils used in these experiments.

Another effect of water on permeability is the tendency to emulsification. When oil is forced out of capillary spaces into larger water-filled channels, the oil mixes with the water as tiny microscopic bubbles. These tiny bubbles of kerosene tend to cling together in the smaller passageways expecially if microscopic particles of clay are present (41) and water by-passes them through the larger openings, increasing the water ratio and lowering the permeability of the smaller passageways to oil flow. This effect appears to be demonstrated by experiments where equal quantities of water and kerosene are in the sand as shown in Table VII.

The effect of water on the permeability of oil is shown in column 5. The relative high percentage of water over oil shown in columns 6 and 7 is regarded by Leverett (21) as best explained by emulsification. This appears to be confirmed by the results with surface-active chemicals. Table VII shows that after the water in the cores is treated with a surface-active chemical which tends to prevent emulsification by lowering the surface tension of water, the percentage of kerosene is increased and the percentage of water reduced as shown in columns 9 and 10. The increase of oil over water after treatment with surface-active chemicals appears to be much greater in kerosene-water mixtures than in crude oil-water mixtures. This may be due to the fact that emulsification agents are present in crude oil which tend to produce fairly stable emulsions of water-in-oil (39). These agents are not present, probably, in refined kerosene. Kerosene with water in the presence of fine clay particles such as occur in the fine-grained sand from Flour Bluff tends to form emulsions of kerosene-in-water (41). Such an emulsion possibly yields a larger percentage of the oil portion than the normal type of emulsion.

DETERMINATION OF POROSITY

Method.—A modified specific-gravity method (5, 24) for determining the porosity of large samples has been devised.

$$\text{Per cent porosity} = \frac{\text{Pore volume}}{\text{Bulk volume}} \times 100.$$

The bulk volume is determined in a special type of picnometer flask illustrated in Figure 8. The apparatus consists of a large glass bottle, from which the bottom has been removed, inverted in a $\frac{1}{4}$-inch pipe support. The bottle is fitted with a one-hole rubber stopper through which a small diameter glass tube, T, is inserted.

The upper end of the glass pipe is bent to fit the shape of the walls of the bottle and reaches to within $1\frac{1}{2}$ inches of the upper edge of the inverted bottle. The lower end of the glass tube is closed with a stop-cock, S. The bottle is filled with the same fluid which is used in measuring the permeability of the core samples, for example, kerosene. The stop-cock in the tube is opened and the excess fluid drained off into a beaker, C. Fifteen to 20 minutes is required for complete drainage. The stop-cock is then closed and a weighed flask inserted underneath the glass tube. The core, thoroughly saturated with fluid as a result of the permea-

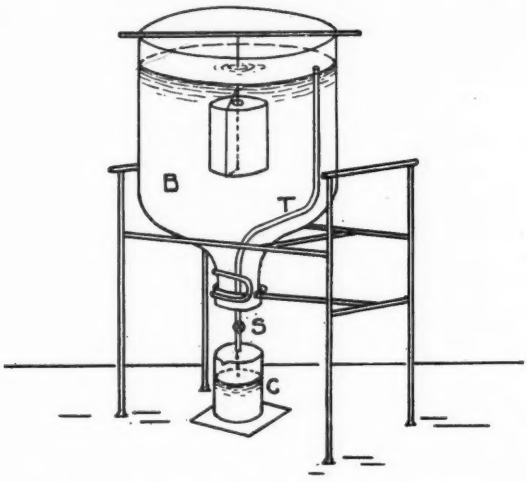

FIG. 8.—Apparatus used in measuring volume of core.

bility measurements, is first weighed in air, then suspended in the fluid by means of a thread as illustrated in the figure. If any air bubbles adhere to the sample, they should be removed by a fine wire, which is kept suspended in the bottle during the entire procedure. The stop-cock is opened and the fluid allowed to drain into the weighed flask. As soon as draining has ceased, the fluid in the flask is weighed on sensitive chemical balances and the volume of the displaced fluid calculated by dividing the weight of the fluid by the specific gravity of the fluid. The specific gravity is easily determined by means of a Westphal balance (13, p. 618).

Calculation of results.—The pore volume is determined by subtracting the weight of the core dry, after it has been extracted with solvent and dehydrated for 24 hours as previously described (Fig. 1), from the weight of the core thoroughly saturated with liquid as a result of the permeability measurements, and then dividing the remainder by the specific gravity of the fluid in the pores. The simple calculations may be summarized as follows.

$$\text{Per cent porosity} = \frac{\text{Pore volume}}{\text{Bulk volume}} \times 100$$

$$\text{Bulk volume} = \frac{\text{Volume of displaced fluid}}{\text{Specific gravity of fluid}}$$

$$\text{Pore volume} = \frac{\text{Weight of saturated core} - \text{Weight of cleaned and dehydrated core}}{\text{Specific gravity of fluid}}$$

Before weighing the wet core in air, the excess fluid on the outside of the core should be quickly wiped off with an absorbent filter paper so that the core will not drip. If the core is a permeable sandstone and tends to drain out while weighing, it is best to weigh it in water and calculate its weight in air by the following formula.

$$\text{Weight in air} = \text{Density of fluid} \times \text{Bulk volume} + \text{Weight in fluid}$$

Discussion of results.—Results obtained by this method measure only the effective porosity of the pores which are connected and open enough so that they are reached, dehydrated, and filled again with the fluid used in the test. The method, however, is rapid and easy to perform provided the cores have already been dehydrated and weighed when preparing the sample for permeability measurements. If this step has not been taken, then it is simpler to cut several small fragments from the core, clean them in a Soxhlet extractor, and determine the porosity by the Russell flask method (4, 17, 28).

A comparison of porosity determinations made by this method using large cores and others made by the Russell flask method, using small chunks cut from the same cores is given in Table VIII.

TABLE VIII

Glen Rose Limestone, Bell County, Sample Number	*Porosity*	
	Determined by Large Picnometer Method Per Cent	*Determined by Russell Flask Method Per Cent*
2	20.01	16.15
3	18.80	18.42
9	20.06	16.08
13	22.12	22.9
16	19.91	19.0

All the large samples were cylindrical-shaped, 2×3 inches, and the small samples were 2-cm. cubes cut out of the large cores. Therefore, a direct comparison is not possible. The results indicate, however, that, due to the irregular porosity of limestone cores, a slightly larger percentage of larger pores are present in the large sample. It is quite possible, however, that the large cores as a result of the permeability measurements are more completely saturated with the fluid than are the small chunks which are dried, evacuated, and saturated during a com-

paratively short time with acetylene tetrachloride in a flask, under only partial vacuum.

DETERMINATION OF SPECIFIC GRAVITY

The specific gravity of the cores is determined (24, p. 49; 13, p. 619) by weighing the sample dry in air before the permeability measurements are made and then weighing it suspended by a thread on the beam of a sensitive balance in the fluid after it has been completely saturated by the permeability tests. Then the specific gravity is determined from the following equation.

$$\text{Sp. gr. of core} = \frac{W_d}{V_s} = \frac{W_d}{\frac{W_d - W_s}{D}} = \frac{W_d \times D}{W_d - W_s}$$

W_d = Weight of dry sample in air after extraction with solvent and dehydration.

V_s = Volume of sand grains.

W_s = Weight of sample when suspended in fluid used for permeability measurements.

D = Density of fluid used, determined with Westphal balance.

Table IX shows the results of specific-gravity measurements made in this way.

TABLE IX

Sample Number	*Formation*	*Location*	*Depth (Feet)*	*Specific Gravity*	*Porosity (Per Cent)*	*Determined by*
2	Glen Rose	U. S. Army core tests, Maxdale district, Bell County	20.5	2.619	16.15	E. Merkt
4	Do.	Do.	25	2.677	17.33	Do.
5	Do.	Do.	40.5	2.692	18.83	Do.
7	Do.	Do.	22.5	2.700	18.22	Do.
10	Do.	Do.	33.25	2.677	17.87	Do.
14	Do.	Do.	44.5	2.665	17.02	Do.
16	Do.	Do.	28.5	2.530	—	Do.
17	Do.	Do.	35	2.621	16.03	Do.
18	Do.	Do.	26	2.642	—	Do.
19	Do.	Do.	39	2.609	16.4	Do.
21	Do.	Do.	32.0	2.621	13.62	Do.
22	Do.	Do.	33.5	2.691	16.18	Do.
		Average of samples = 2.646				
	Woodbine sand	East Texas oil field	—	2.66	—	Wm. Terry
	Travis Peak sand	U. S. Army water well, Belton, Bell County	—	2.67	—	Do.
	Trinity sand	Thompson No. 3, Limestone County	—	2.69	—	Do.
	Austin chalk	Austin, Travis Co.	—	2.35	—	Do.
	Edwards limestone	Chesterburg No. 4 well, Caldwell Co.	—	2.70	—	Do.
	Marble Falls limestone	Outcrops in Llano area; av. of 10 samples	—	2.64	—	Do.

TABLE IX (*Continued*)

Sample Number	*Formation*	*Location*	*Depth (Feet)*	*Specific Gravity*	*Porosity (Per Cent)*	*Determined by*
1	Edwards limestone	United North & South Barron-Crenshaw No. 1, Caldwell County	2,249	2.69	33.55	Wm. Terry & R. B. Newcome
2	Do.	United North & South Cartwright No. 2, Caldwell County	2,197	2.76	12.28	Do.
3	Do.	United North & South Chester Byrd No. 1, Caldwell County	2,127	2.70	29.80	Do.
4	Do.	United North & South Cartwright No. 2, Caldwell County	2,182	2.74	33.20	Do.
5	Do.	United North & South A. H. Mercer No. 2, Caldwell County	2,110	2.74	28.72	Do.
6	Travis Peak	Pure Oil Co., Thompson No. 3, Limestone County	5,770	2.68	14.3	Do.
7	Do.	U. S. Army, Bruner No. 1, Bell County	729	2.41	14.3	Wm. Terry
8	Do.	Do.	731	2.42	13.5	Do.
9	Marble Falls	T. & P. Oil Co., Norwood No. 33, Erath County	3,458	—	7.35	R. B. Newcome
10	Do.	Do.	3,363	—	20.68	Do.
11	Do.	Do.	3,461	—	18.00	Do.
12	Do.	10 samples, average	—	2.64	—	Wm. Terry
1	Woodbine sand	Sun Oil Co., Selman No. 1, Rusk County	3,701	2.68	23.92	Wm. Terry & R. B. Newcome
2	Do.	Gulf Prod. Co., Fanville No. 1, Gregg Co.	3,555	2.64	24.10	Do.
3	Do.	Humble Oil Co., Milliken No. 7, Rusk Co.	3,612	2.67	—	Wm. Terry
4	Do.	Shell Pet. Co., Tunnell No. 2, Van Zandt County	2,426	2.60	32.00	Wm. Terry & R. B. Newcome
5	Do.	Vacuum Oil Co., Beaver No. 2, Gregg Co.	3,521	2.65	21.85	Do.
6	Do.	Cranfill & Reynolds, Young B-1, Rusk Co.	3,659	2.65	18.98	Do.
7	Do.	Shell Pet. Co., Tunnell No. 1, Van Zandt County	2,550	2.78	26.80	Do.
8	Do.	Gulf Prod. Co., Brightwell No. 5, Gregg Co.	3,623	2.68	27.50	Do.
9	Do.	Vacuum Oil Co., Stinkcomb No. 3, Gregg Co.	3,568	2.64	22.80	Do.
10	Do.	Vacuum Oil Co., Tate No. 7, Gregg Co.	3,460	2.65	24.50	Do.
1	Strawn sandstone	Echo district, Coleman County	1,950	2.668	24.6	W. J. Murray
2	Do.	Do.	Do.	2.667	24.6	Do.
3	Do.	Do.	Do.	2.670	24.4	Do.
4	Do.	Do.	Do.	2.667	24.2	Do.
5	Do.	Do.	Do.	2.668	24.4	Do.
6	Do.	Do.	Do.	2.666	23.8	Do.
7	Do.	Do.	Do.	2.668	24.5	Do.
8	Do.	Do.	Do.	2.668	24.3	Do.
9	Do.	Do.	Do.	2.666	23.8	Do.
10	Do.	Do.	Do.	2.670	23.6	Do.
		Average of 10 samples=		2.668	24.2	

SUMMARY OF TECHNIQUE

Experience indicates that best results are obtained when cores are tested as nearly as possible under original reservoir conditions with the least possible change in reservoir fluids or in the rock itself. (1). The core should be obtained whenever possible by using oil for drilling mud, and not water, when coring. (2). The core should be handled as little as possible, cut or fractured as little as possible, and sawed, washed and tested by using only original reservoir fluid or fluid very similar to that in the core. (3). In testing limestone samples, large cores are preferable to small ones. (4). Removal of the oil and dehydration of the core are not necessary, if these precautions are heeded and if a fluid similar to that in the interspaces is used for all the flow tests. (5). Determination of fluid content can be made by using separate adjacent chunks by either the Soxhlet or pressure-displacement method.

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GEOLOGICAL NOTES

EVIDENCE OF EROSION OF SALT STOCK IN GULF COAST SALT PLUG IN LATE OLIGOCENE[1]

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In the examination of a suite of cuttings from the Gulf Oil Corporation's Ehlert No. 1, near Needville, Fort Bend County, Texas, the writer found a few grains of anhydrite of the type which is characteristic of the 5–10 per cent of disseminated anhydrite found in the salt stocks of Gulf Coast salt domes.[3] Since this type of anhydrite has not been noted in the Gulf Coast except in association with salt, this finding was of considerable interest. If the grains found at the given depth belonged in the sediments at this depth, it would have been necessary to postulate the active erosion of a salt plug sufficiently near to allow for the anhydrite to be transported to the site of the well. Such a postulation, in this particular case, did not seem reasonable.

Several samples were examined below the first occurrence and additional anhydrite grains were found. Casing had been set immediately above the first occurrence. The samples above the casing seat had been examined in detail and no anhydrite had been found. Sodium silicate mud was introduced immediately after the casing was set. All the chemicals used in the mud were checked for anhydrite, but none was found. Several pounds of sodium silicate were examined. On further inquiry it was found that about 50 pounds of salt from one of the Gulf Coast salt domes had been added to the mud in the mixing with sodium silicate. Since disseminated anhydrite seems to be universal in Gulf Coast salt plugs, any mined unrefined salt from these plugs, when added to drilling mud, would allow for anhydrite grains in the cuttings. The reason for anhydrite in the cuttings at Needville was considered to have been found.

The writer published a note, "Evidence of Erosion of Salt Stock in Gulf Coast Salt Plug in Late Oligocene,"[4] in 1939. The evidence, in this case, was the presence of anhydrite grains in the cuttings from a well in Brazoria County, Texas. This information has been reexamined in the light of the findings at Needville. Sodium silicate mud was introduced in the Brazoria County well shortly above the depth at which the anhydrite grains were found. It is assumed salt was used in this mud also. Because of this it must be concluded that the anhydrite found was from contamination in the mud and not from the erosion

[1] Published with permission of the Gulf Oil Corporation. Manuscript received, November 19, 1942.

[2] Geological department, Gulf Oil Corporation.

[3] Marcus A. Hanna, "Geology of the Gulf Coast Salt Domes," *Problems of Petroleum Geology* (Amer. Assoc. Petrol. Geol., August, 1934), Pl. III, Figs. 1–4.

[4] Marcus A. Hanna, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 23, No. 4 (April, 1939), pp. 604–07. *Ibid.*, Vol. 23, No. 10 (October, 1939), p. 1576.

of a salt stock as postulated. The object of this note is to correct this mistake.

The cross sections of Orchard dome, Fort Bend County, and Hawkinsville dome, Matagorda County, Texas, given in the aforementioned note[5] very definitely indicate that domes have been actively eroded. Others might be cited. Definite anhydrite grains from such erosion, however, must now await future discovery.

Care must be taken in watching for such anhydrite grains to be certain that sodium silicate mud has not been used in any particular well, and that mud from other wells in which sodium silicate mud was used was not hauled to the particular well and reused.

[5] *Ibid.*, p. 605, Figs. 1–2.

GEOPHYSICAL INVESTIGATIONS IN TRI-STATE ZINC AND LEAD MINING DISTRICT[1]

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Early in 1941 the University of Kansas Engineering Experiment Station and the State Geological Survey of Kansas were invited, by several governmental agencies, to investigate the feasibility of using geophysical methods as a guide to ore prospecting in the Tri-State zinc and lead mining district of Kansas, Oklahoma, and Missouri. The increased demand for zinc and lead in the production of war materials made it appear desirable to attempt to develop some geophysical method or combination of methods which would be more rapid and less expensive than the present method of exploration by churn drilling now commonly employed in the Tri-State district.

A cooperative agreement was made between the Engineering Experiment Station, the State Geological Survey, and the Tri-State Zinc and Lead Ore Producers' Association whereby the project was financed by the three organizations.

In order to simplify the initial experimental work, all the geophysical investigations were made over areas where, as the result of intensive drilling, the geologic conditions and mode of ore occurrence were already known. In each area there was an attempt made to correlate the various geophysical anomalies with known geologic conditions. No attempt was made to prospect areas which had not been explored by drilling. This work will constitute the second period of investigation and will be undertaken shortly.

During the course of the investigation, the following types of geophysical surveys were conducted: electrical resistivity, geothermal, geochemical, gravity, natural earth potential, and magnetic. Results obtained in this investigation

[1] Manuscript received, December 8, 1942.

[2] University of Kansas.

indicate that the geochemical, geothermal, and natural earth potential are negative as regards their diagnostic value in the delineation or location of ore bodies in that area.

The magnetic work gave results that are regional in character, and which are indicated as being useful as a guide in the interpretation of regional gravity anomalies.

The indications given by the regional gravity survey that regional gravity maxima are present and are deep-seated (as indicated by coincidence with regional magnetic maxima) make it appear advisable to recommend further regional gravity investigations. It appears possible, in the Mississippi Valley area, to separate potential zinc-lead producing areas from potentially non-productive areas, by the presence or absence of deep-seated gravity maxima.

Resistivity and gravity measurements can be used successfully to map structures reflected by variations in the elevation of the limestone surface. It is not possible geophysically to map structures within the limestone.

It has not been found possible, directly, to determine the presence of lead and zinc sulphides. It is possible, however, to use resistivity measurements in mapping certain structural and lithologic features associated at many places with ore mineralization, especially increased porosity of the limestone resulting from fracturing and brecciation. Such measurements, therefore permit the selection of ground which might have productive possibilities, although an area could not definitely be classified as non-productive because of the absence of resistivity minima, or as necessarily productive because of the presence of resistivity minima. The judicious use of resistivity methods, however, should serve greatly to minimize the amount of exploratory drilling required, by directing drilling to the most favorable prospecting areas. On the average, a saving of only one drill hole would pay for the cost of conducting detailed resistivity work over an area of 10–20 acres. The present normal prospecting procedure, using drills, would require many hundreds of drill holes over such an area. Moreover, additional resistivity investigations have revealed methods of determining ore mineralization, which are described in more detail in the bulletin now in press.

Copies of the final bulletin may be obtained by directing a request to the Director, Engineering Experiment Station, University of Kansas, Lawrence, Kansas.

EXAMPLE OF DIRECTIONAL DRILLING AS APPLIED TO GEOLOGY IN ELLIS COUNTY, KANSAS[1]

R. L. CLIFTON[2]
Enid, Oklahoma

The Champlin Refining Company completed a dry hole, in May, 1941, at its No. 11-D, N. ½, SW. ¼, SW. ¼ Sec. 17, T. 11 S., R. 17 W., Ellis County, Kansas.

[1] Manuscript received, September, 1942.

[2] Geologist, Champlin Refining Company.

The Arbuckle formation was encountered by the drill in this well at a depth of 3,635 feet, or at a sea-level datum of −1,708 feet.

Because of certain subsurface factors, related to Arbuckle topography and to geologic structure in this area, it was decided to redrill the 11-D Hadley by a method of directional drilling, in the endeavor to encounter Arbuckle strata at some sea-level datum high enough for possible commercial production from the Arbuckle formation.

Accordingly, it was planned to begin the deflected drill hole at a point about 1,500 feet below the surface, in the 11-D drill hole, and to use an average deflection angle of 8° 40′, in a direction N. 38° E. of No. 11-D. The Arbuckle

TABLE I

RECORD OF SURVEY

Measured Depth, in Feet, Deflected Drill Hole	*Angle of Drift*		*Direction of Drift in Degrees East of North*
	Degrees	*Minutes*	
1,388	0	00	Vertical
1,414	3	10	60
1,479	5	10	63
1,468	6	30	63
1,658	7	40	58
1,778	7	15	42
1,868	8	45	44
1,968	11	40	43
2,108	11	30	39
2,262	11	00	39
2,440	11	10	38
2,780	10	20	36
3,050	10	10	36
3,140	8	15	42
3,230	7	00	49
3,330*	5	00	53
3,400*	3	00	56
3,480*	2	00	56

* Angle estimated.

formation, as calculated for such angles, should be expected in the deflected drill hole at a maximum slope depth of 3,490 feet, or at a calculated derrick-floor vertical depth of 3,468 feet, and in a direction 300 feet N. 38° E. of the 11-D location.

Directional drilling at the 11-D location was begun in August, 1941. Work proceeded satisfactorily by the use of whipstocks, directional surveys, and skillful rotary drilling technique, under the direction of the Eastman Oil Well Survey Company of Oklahoma City, Oklahoma, to a successful completion, in September, 1941.

The Arbuckle formation was encountered in the deflected drill hole at a slope depth of 3,466 feet, by the use of an average deflection angle of 9°, and in the direction 314.5 feet N. 41° 32′ E. of No. 11-D. The derrick floor vertical depth for the point at which the Arbuckle formation was encountered in the deflected drill hole is 3,441 feet, or a sea-level datum of −1,514 feet.

Economies effected by the use of directional drilling as against an alternative

of moving drilling equipment to a new location, to proceed by usual rotary drilling methods, were important. It was possible to utilize surface casing, already cemented in the old drill hole, to use pits, cellar, derrick, and other items, having important usage, if not salvage values.

In brief, geologic structure of the Burnett-Bemis-Shutts oil pools of northeastern Ellis County, Kansas, may be typified as a broad uplift, or structural

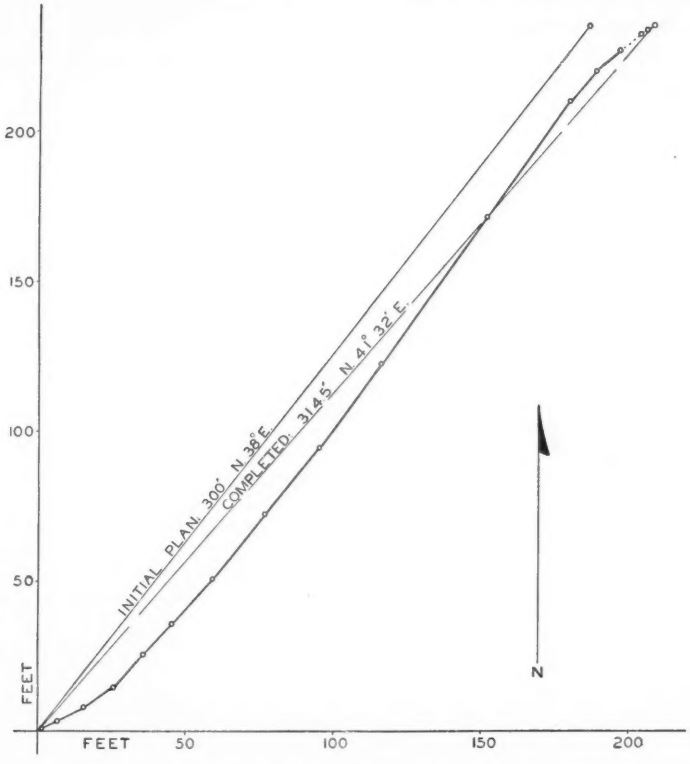

FIG. 1.—Plane projection for drill-bit course, to illustrate directional and deflection angles, No. 11-D Hadley.

plateau of low structural relief. Minor folds or flexures, likewise of low relief, are present on the gently folded uplift. The area of uplift has been eroded and is deeply dissected by channels or old stream courses. Erratic change in interval between basal Pennsylvanian and Arbuckle strata, from one well location to another, is not exceptional. This fact is demonstrated by development at the No. 11-D Hadley location (Table I and Fig. 1).

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VOL. 27, NO. 1 (JANUARY, 1943), PP. 90–91

DISCUSSION

REGIONAL GEOLOGY OF DAKOTA BASIN[1]

W. C. Howells.[2]—In the last paragraph of his paper on the "Regional Geology of Dakota Basin," Norval Ballard suggests that the Williston basin extends northwestward from North Dakota and continues into northeastern British Columbia. This, I am sure, will not find ready acceptance in the minds of students of geology familiar with the regional stratigraphic and structural geology of western Canada. Mr. Ballard states,

> The North Dakota Williston basin continues northwestward into northern Alberta and northeastern British Columbia. Oil and gas have been produced on the southwest side of this basin at Turner Valley, Bow Island, Medicine Hat, and Foremost. On the north flank of the Canadian extension of the basin, oil and gas are produced on the Athabaska River, Peace River, Battle River, and at Viking.

To discuss a few lines in any paper would usually be considered unworthy, but the implication is so far-reaching in its dismissal of presently held opinions that it is not advisable to have it remain in the literature uncontested. Although the regional geological data of western Canada is meager, there is sufficient evidence to refute the supposition of a single major structural depression trending northwestward through the Canadian plains, and to predicate with confidence the existence of two widely separated basins, namely, the Rocky Mountain geosyncline and the northward extension of the Williston basin into Saskatchewan, which are not connected, at least in Canada, to form a structural entity. During certain periods, seas were sufficiently widespread to cover the whole of the Canadian prairie provinces, but there is no evidence to indicate that the aforementioned structural depressions were otherwise connected.

No consideration will be given to structural or stratigraphic details since only a few notes are necessary to point out the error. Sufficient surface and subsurface information is available to prove the presence of a wide homoclinal belt, immediately south of the pre-Cambrian shield, which forms the northern flank of the Williston basin in Saskatchewan and the eastern flank of the Alberta syncline in Alberta. Beds tentatively assigned to the Devonian are somewhat thicker near Wainwright than on the north or south, suggesting the possible existence of a localized sedimentary basin in east-central Alberta during Devonian or pre-Devonian time. It is quite possible that such a depression might represent an extension of the Williston basin into eastern Alberta. At the end of Jefferson (?) time, however, all semblance of this basin structure is absent, and subsurface information indicates a gradual dip toward the south, which is interpreted as being a component of the southwesterly dip into the Alberta syncline.

Westward from Wainwright the beds dip generally southwest. East and south in Saskatchewan the strata, according to present information, dip generally east and southeast. It appears from the thickening of sediments toward the west and southeast from east-central Alberta, and the absence of certain sediments in that area, that this general region was relatively high compared with areas at the east and west perhaps since pre-Cambrian time. The oil and gas fields mentioned in the foregoing quotation, with the exception of Turner Valley, are located on the eastern flank of the Alberta syncline, and not on the southern and northern flanks of the northwestern extension of the Williston basin. Due to structural complications it is difficult to assign the position of Turner Valley

[1] Original article of this title, by Norval Ballard, published in this *Bulletin*, Vol. 26, No. 10 (October, 1942), pp. 1557–84.

[2] McColl-Frontenac Oil Company Limited, Lancaster Building, Calgary, Alberta. Manuscript received, November 30, 1942.

with reference to the formerly existing Rocky Mountain sedimentary trough although it is quite probable that the producing zones of Turner Valley originally occupied a position on the lower part of the eastern flank of this geosyncline.

JOSEPH S. IRWIN.[3]—W. C. Howells has kindly afforded me the opportunity to read the manuscript of his discussion of Norval Ballard's paper, "Regional Geology of Dakota Basin."

I agree with Howells that Ballard's concept of the Williston basin as extending into northern Alberta and northeastern British Columbia, and the implied identity of the Williston and Alberta synclines are not in accord with the facts.

The Williston basin and its northern extension, the Moosejaw syncline, are structurally separated from the Alberta syncline by the Sweetgrass arch. Northward in Saskatchewan and Alberta both the Williston-Moosejaw syncline and the Sweetgrass arch fade and merge into a southwestward-dipping homocline which, in northern Alberta and thence northwestward, becomes the east flank of the Alberta syncline.

The structural situation has been illustrated in both plan and vertical section.[4] The relief between the southern part of the Moosejaw syncline and the Sweetgrass arch is materially greater than that shown in the published structure section, as indicated by results now being obtained in the Norcanols well drilling near Radville, 70 miles south of Regina, Saskatchewan, in the Moosejaw syncline. The pre-Cambrian is more than 5,500 feet below sea-level, rather than 4,300 feet below sea-level as indicated in the section. On the Sweetgrass arch, at the latitude of the section, the pre-Cambrian is found at 3,700 feet below sea-level.

Notwithstanding the structural inadvertence, Ballard is correct in pointing out that the same petroliferous, and in places commercially productive, formations occur throughout the region.

NORVAL BALLARD.[5]—It is not literally true that the north extension of the Williston basin is the Great Plains geosyncline of western Canada. A more accurate but still not satisfactory statement is that the Williston-Moosejaw syncline, the Alberta-Calgary syncline, and the intervening Sweetgrass arch all form the entity known as the Great Plains geologic province of western Canada. Likewise this broad Canadian feature is only a part of the much larger Rocky Mountain geosyncline extending across the United States. This geosyncline is roughly bounded by the distribution of the Cretaceous strata. It was the Canadian part of this broad geological feature that the writer had in mind in the last paragraph of the article, referred to in the discussion by W. C. Howells.

[3] Consulting geologist, 812 Lancaster Building, Calgary, Alberta. Manuscript received, December 2, 1942.

[4] *Possible Future Oil Provinces of the United States and Canada*, Amer. Assoc. Petrol. Geol. (1941), pp. 16 and 17, Figs. 1 and 2.

[5] Consulting geologist, 1105 Northeast Twentieth, Oklahoma City, Oklahoma. Manuscript received, December 12, 1942.

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REVIEWS AND NEW PUBLICATIONS

* Subjects indicated by asterisk are in the Association library, and are available, for loan, to members and associates.

STRATIGRAPHY OF NORTHERN SOUTH AMERICA, TRINIDAD, AND BARBADOS, BY H. H. RENZ

REVIEW BY HUBERT G. SCHENCK[1]
Stanford University, California

"Stratigraphy of Northern South America, Trinidad, and Barbados," by H. H. Renz, *Proceedings Eight American Scientific Congress, 1940*, Geological Sciences, Vol. 4, pp. 513–71; 1 correlation chart, 113 bibliographic references. Washington, D. C. (1942).

The only adequate way to review this paper would be to copy it, so condensed is the important contribution which assembles many disseminated data heretofore unpublished or published in sources not readily available to workers in general. The remarks to follow, it is hoped, will direct readers to the article, and especially to the detailed correlation chart accompanying it. One may make instructive comparisons of this chart with Senn's compilation in this *Bulletin*, Vol. 24 (1940), pp. 1548–1618, and with the chart by Kugler and others in Vaughan and Cole, *Geological Society of America Special Paper 30* (1941).

Although pre-Cambrian and Cambrian rocks are reported in several localities in the highlands of Guayana, Caribbean Coastal Range, Colombia, and the Andes of western Venezuela, the determinations of the ages of the rocks are doubtful. Shales with Ordovician graptolites (*Dicanograptus* and *Cryptolithus*) constitute a part of the Caparro "series" of the Andes of western Venezuela; similar shales occur in the Central Cordillera of Colombia. Devonian formations are the most widely distributed of all Paleozoic deposits in South America. Marine Carboniferous strata crop out in Venezuela and Colombia. The most northerly occurrence of the Gondwana type "Permian" deposits is in northeastern Brazil.

Rocks of Mesozoic age have been studied in many places throughout the region. The only marine Triassic strata known to date are on the eastern side of the Central Cordillera in the Magdalena Valley, Colombia, suggesting that the Norian (Upper Triassic) sea invaded from the direction of Peru. Marine Upper Jurassic beds occur in Trinidad; elsewhere the Jurassic sediments appear to be chiefly non-marine. Neocomian formations —to and including the Aptian stage—are present in Colombia, Venezuela, and Trinidad. Hauterivian ammonites have been collected in the Suárez formation of Colombia.

The long marine sedimentary record of much of the region begins in Aptian time. Of particular interest is *Neohibolites aptiensis* and other Aptian species of this genus of gelemnites in the Maridale marl (omitted from chart) of Trinidad. Cenomanian fossils occur in Colombia, Venezuela, and Trinidad. The presence of Turonian and Coniacian strata is proved by cephalopod faunas listed by Gerth from Colombia; elsewhere the paleontologic evidence for the recognition of strata of these two stages seems to be unsatisfactory. Under the caption "Santonian, Campanian, Maestrichtian, Danian" are listed several formations in Colombia, Venezuela, and Trinidad. Among the many noteworthy facts is the discovery by Hedberg of *Sphenodiscus* and *Coahuilites*, Maestrichtian indicators, in the Rio Oro formation of the western Maracaibo basin.

That the line between the Cretaceous and Tertiary passes through several formations is one of the interesting features of the chart. The author makes this important statement (page 531):

[1] Manuscript received, December 10, 1942.

Between the Cretaceous and the Tertiary there is apparently no break in sedimentation and no major unconformity exists in northern South America.

Micropaleontologists will learn with profit that the foraminifers described by Cushman and Jarvis (*Proc. U. S. Nat. Mus.*, Vol. 80, Art. 14 (1932), pp. 1–60) from Trinidad originated from at least four different localities. Three of the localities are beds of late Cretaceous age; one is Paleocene. That is to say, the lower Lizard Springs beds are Cretaceous; the upper Lizard Springs beds are Paleocene.

One of the better known formations in the New World is the Soldado formation, typically exposed on the small island of Soldado Rock between the southwest coast of Trinidad and the Pedernales coast of Venezuela. An excellent description of the formation is given by Kugler (slightly modified) in Vaughan and Cole, previously cited. Renz holds that this formation is Paleocene; so do many other writers. Another exposure of the Soldado is at the Marac quarry in South Trinidad, where an exceptionally fine molluscan fauna has been collected. Among the species is a member of the famous "*Venericardia beaumonti* group" of pelecypods, so admirably reviewed by Rutsch (*Eclogae Geologicae Helvetiae*, Vol. 29, No. 1 (1936), pp. 187–207).

In Trinidad, the lower Navet formation is believed to be of early Eocene age, the correlative of the Wilcox of the Gulf Coast and the Aragon of Mexico. The upper Navet formation is middle Eocene. Some of the foraminifers are *Anomalina dorri* var. *aragonensis* Nuttall, *Globorotalia aragonensis* Nuttall, *Hantkenina* cf. *mexicana* Cushman, and *Hantkenina lehneri* Cushman and Jarvis. The Scotland formation of the Barbados has the same time span as the Navet.

Formations dated as late Eocene (Jacksonian) are more widespread than the other Eocene divisions. One of the formations under the caption Upper Eocene is the San Fernando formation of Trinidad. Among the smaller foraminifers in it are *Bulimina jacksonensis* Cushman, *Hantkenina alabamensis* Cushman var. *primitiva* Cushman and Jarvis,[2] and *Uvigerina curta* Cushman and Jarvis. *Tubulostium*—the "*Spiroglyphus*?" of California workers—occurs both in the middle and upper Eocene of this region. The Oceanic formation of Barbados is middle or upper Eocene and Oligocene.

Oligocene formations occur in many localities. The Oligocene-Miocene boundary is placed within several of the formations. For example, the Agua Salada formation of eastern Falcón, Venezuela, is late Oligocene at its base and Miocene above. The same is true of the Brasso formation of Trinidad. The lower member of the Brasso formation, the Esmeralda member, is middle to upper Oligocene; it has yielded a large fauna including such foraminiferal species as *Bolivina pisciformis* Galloway and Morrey, *Cassidulina carapitana* Hedberg, *Cibicides floridanus* (Cushman) var. *compressa* Cushman and Renz, *Siphogenerina transversa* (Cushman), and *Uvigerina gallowayi* Cushman var. *basicordata* Cushman and Renz. Stratigraphically higher, the Miocene part of the Brasso formation is exceedingly rich in microfossils, among which may be mentioned *Amphistegina lessonii* d'Orbigny, *Bolivina floridana* Cushman, *Bolivina marginata* Cushman, *Bulimina rinconensis* Cushman and Laiming, *Cancris sagra* d'Orbigny, *Plectofrondicularia californica* Cushman and Stewart, *Pseudoglandulina gallowayi* Cushman, and *Siphogenerina lamellata* Cushman. Unconformable above the Brasso formation is the Springvale formation with many megafossils and a fairly rich foraminiferal assemblage. The Springvale formation is thought by Rutsch to be upper Miocene.

Attention is drawn to the Oligocene Cipero formation of southern Trinidad. At the base occur abundant specimens of *Lepidocyclina* (*Lepidocyclina*) *yurnagunensis* Cushman. In the middle part of the formation are *Lepidocyclina* (*Lepidocyclina*) *supera* (Conrad),

[2] H. E. Thalmann, "Foraminiferal Genus *Hantkenina* and Its Subgenera," *Amer. Jour. Sci.*, Vol. 240 (1942), pp. 809–20, treats *primitiva* as a species of the subgenus *Hantkenina, sensu stricto*, a subgenus which ranges from the Lutetian to Wemmelian, inclusive.

L. yurnagunensis, and *L. yurnagunensis morganopsis* Vaughan, together with *Lepidocyclina (Eulepidina) favosa* Cushman. Associated with the lepidocyclines are megafossils, such as *Turritella* aff. *altilira* Conrad. From the upper member of the Cipero formation at Freeman's Bay, Rutsch has identified a number of upper Oligocene mollusks, among which are *Thyasira adoccasa* van Winkle and *Pleurophopsis unioides* van Winkle.

As during Eocene and Oligocene times, the deposits during the Miocene were formed in the sea near the present north coast of Colombia, whereas in the Magdalena Valley the formations are estuarine, fresh water, and continental. The marine "Las Perdices Group" in Colombia is upper Oligocene in its lower part, according to A. A. Olsson, but F. M. Anderson called the "group" lower Miocene. The superjacent Tubera "group" is middle Miocene, the correlative of the Gatun formation of the Panama Canal Zone. Still higher is the Usiacuri formation with a fauna suggestive of late Miocene age. The Springvale formation of Trinidad at its base contains a rich molluscan fauna. The Lengua beds of southern Trinidad have yielded an exceptionally varied Miocene foraminiferal assemblage.

Pliocene coral limestones and clastic rocks of the coast of Colombia attain a thickness locally of 900 feet. The non-marine Mesa formation of the Magdalena Valley consists of 1,000 feet of sands and andesitic tuffs. In the western Maracaibo basin the non-marine Onia beds aggregate about 5,000 feet in thickness. The well known Punta Gavilan formation of eastern Falcón contains many megafossils, but it is undecided whether to date the formation as late Miocene or Pliocene. The Talparo formation in Trinidad is possibly Miocene in the lower marine part; the upper, brackish-fresh part is Pliocene. Pleistocene strata are recognized in Colombia, Venezuela, Trinidad, and Barbados.

The reviewer now takes the liberty of making a few comments on this valuable contribution. He does so for the benefit of those who might read the review, not for the benefit of Dr. Renz, as an interchange of letters and specimens has shown that the author and reviewer mutually understand and appreciate the many unsolved problems and difficulties to be overcome before reaching satisfactory conclusions regarding the ages of all of the formations. Nor are the remarks made for the reason that geologists must be told of the obvious need for further study in critical areas. Rather is the reader's attention directed to certain broad-scale relationships brought to the fore by the investigations of modern biostratigraphers.

The significant conclusion that apparently no break in sedimentation took place at the close of Cretaceous time in the area covered in this report finds a parallel in some localities in California and in other parts of the world. For example, in the vicinity of the Panoche Hills on the west side of the San Joaquin Valley, California, detailed studies of both surface and subsurface sections leave workers doubtful as to exactly where to place the Cretaceous-Tertiary boundary. Continuous sedimentation from the Cretaceous to the Paleocene is also true in the interior of the United States and Canada in more than one district. In Baluchistan, Noetling (*Central. f. Min., Palaeon., etc.* (1903), p. 515) showed that locally no unconformity separates the Cretaceous and Tertiary strata. The literature is too voluminous to cite here. The important conclusion which seems to be overlooked by a few diastrophists is that whereas in some areas an unconformity separates Cretaceous and Tertiary formations, in other areas deposition was continuous. It is in those areas that workers are particularly critical of the paleontologic evidence used in setting the boundary.

Paleontologists are now inclined to agree on placing the entire Soldado formation in the Paleocene. The evidence seems to favor this decision. Nevertheless, specialists are cautious in making a dogmatic assertion of its age. For one thing, they are not certain which beds in the New World are correlative with the type locality of the Danian stage. Second, the biochrons of many species, such as *Siphogenerinoides eleganta* (Plummer), are not positively settled. Third, caution is introduced into paleontologic analyses by reworked fossils. Many other reasons for caution will doubtless come to the reader's mind.

Amazing as it may seem, no paleontologist has prepared an adequate, exhaustive review of the biologic criteria to be used in delimiting the Cretaceous and Tertiary.

A preliminary study of the Maridale marl (Aptian) from Mon Dieu Valley, Trinidad, suggests that instructive comparisons might be made of Caribbean material with the detailed zonation published by Hecht[3] showing the relation between foraminiferal zones and those established through the use of ammonites. The reason why such comparisons might be instructive is that micropaleontologists do not yet know the full geographic extent of the zones founded on foraminifers, even when the zones are properly established time-stratigraphic divisions of stages.

One of the striking results of a comparison of a sequence of foraminiferal samples from Trinidad[4] with sequences from California is the remarkable similarity between the Paleocene and Eocene species of the two regions. That several formations, such as the Agua Salada, with *Siphogenerina transversa*, may prove to have been deposited during the same age as some part of the Culebra of the Canal Zone and as some part of the Zemorrian and Saucesian of California, is also suggested by the comparisons. Detailed study of the smaller foraminifers will doubtless bring to light other suggestive relationships.

In conclusion, the work being carried on by Renz and many others in the critical Caribbean region will properly define the several time-stratigraphic units and will better discriminate them from lithogenetic units. Although called a formation, the Cipero has not been defined as a lithogenetic unit; it is treated as a time-stratigraphic one. This is an example of a detail which should not detract from the major additions to knowledge being made by skilled scientists on oil company staffs.

[3] Franz E. Hecht, "Standard-Gliederung der Nordwestdeutschen Unterkreide nach Foraminiferen," *Senckenbergischen Naturforschenden Gesellschaft*, Abhandlung 443 (1938) pp. 1–42; 24 pls. 4 tables, 1 fig.

[4] The Trinidad Leaseholds, Ltd., Pointe-à-Pierre, Trinidad, through Dr. H. H. Renz, has deposited in the paleontological collections at Stanford University a large amount of useful foraminiferal material and assemblage slides from Trinidad and Venezuela. These may be studied by any micropaleontologist upon request.

AERIAL PHOTOGRAPHS: THEIR USE AND INTERPRETATION, BY A. J. EARDLEY

REVIEW BY LOUIS DESJARDINS[1]
Tulsa, Oklahoma

Aerial Photographs: Their Use and Interpretation, by A. J. Eardley, University of Michigan. Cloth, 203 pp., $2.75. Harper and Brothers (1942). First volume of *Geoscience Series*, Carey Croneis, editor.

This is a very timely book, broadly covering the field of aerial photographs, but with a large enough geological emphasis not only to insure that geologists will be the principal users of the book, but to give them the best and fullest treatment of geological interpretation of aerial photographs yet published in book form. The treatment of many topics, I believe, surpasses that in any other text covering the same subjects in brevity, yet essential completeness.

[1] Aero-Geologist, 739 Kennedy Building. Manuscript received, December 4, 1942.

A review of this book by W. A. Ver Wiebe appeared in the December *Bulletin*. This had scarcely gone to press when the editors received Mr. Desjardins' review, part of which is here published. The parts omitted (with the reviewer's consent) are mainly those giving a synopsis of the book, because it was summarized in December. Following are chiefly the reviewer's criticisms. In singling out these criticisms for publication, it is only fair to state that Mr. Desjardins' review of the book as a whole, and especially of its geological chapters, was one of considerable praise and commendation.—*Editorial comment.*

The author's teaching and laboratory experience have gone into the book, which contains sufficient practical material to serve as a training manual, especially in the geological uses, though it should be supplemented with a larger amount of similar photographic material, especially stereoscopic, to provide a very thorough course.

The chief obvious criticism of the book is the stinginess of illustrative material. The reader is bound to regret that the author of such a fine book had not gone to just a little more trouble and given us about twice the number of photographs, especially since they have been so perfectly reproduced. There is no mention of color photography; also the book has no frontispiece. Hence, I suggest that a striking colored aerial photograph be selected for a frontispiece in any future edition.

The virtual absence of stereoscopic pairs among the illustrations I regard as a most serious oversight. The only stereo-pair printed in the whole book (Pl. 5) is spread too wide for unaided stereoscopic vision or lens-type stereoscopes, and too close for ordinary mirror stereoscopes. Hence, few if any readers or students will ever see it stereoscopically. (Lens-type stereoscopes can be used successfully only with Pl. 8, not intended for any three-dimensional study, in the chapter on mosaics.) My suggestion is to prepare a number of stereo-pairs at slightly under $2\frac{1}{2}$-inch separation (average for users of lens-type stereoscopes), especially in connection with the geological interpretation. Any serious training course in geological interpretation of aerial photographs must be nine-tenths stereoscopic.

The author seems occasionally to have used material borrowed from other sources without checking its accuracy, or without resubmitting it accurately. He quotes from a pamphlet of a private aerial surveys company (p. 18): "all sections of the area flown will appear on four different exposures"; while in fact a large part of the total area appears on only two photographs under the conditions of per cent of overlap given. While the author includes this lengthy quotation from this pamphlet (pp. 14–20) descriptive of a partly non-standard method, he makes no mention of the United States Department of Agriculture or other government standards where they differ.

Another example of copying others' errors is in the diagram purporting to illustrate the principle of the lens-type stereoscope (p. 34). This would have the eyes of the observer converging approximately upon the table top from a height of 3 to 6 inches and would require looking through the insides of the lenses. In reality, this type of stereoscope permits the observer to look through the centers of these lenses in parallel or nearly parallel eye directions. That the author was completely misled is indicated by his statement (p. 37) that for home-made stereoscope lenses "by adjusting them so that the eyes look through the inside part of each lens, stereoscopic vision can be obtained." (The author's attention is called to the correct principle of the lens-type stereoscope in the illustration on p. 28, case No. 4, used by him in another connection.)

Another error, also probably passed on from one author to another, is the statement (p. 50) that the isocenter ("*i*" of Fig. 16) is "the point midway between the principal point *p* and the plumb point *v*." The isocenter can never be midway between these, and *vi* is always greater than *ip*. "*i*" is determined by the bisector of the angle *vOp*, *O* being at the camera lens. The author failed to mention the most important property of the isocenter—that it is the only point through which all straight lines have the same directions on the photograph that they have on the ground. (His ambiguous statement "perspective changes due to tilt are radial from the isocenter" could mean or imply this, however; but such wording is unfortunate because in most minds a "perspective change" would mean a change in viewpoint, not occurring in this case.) His statement that "the axis of tilt . . . is the only line of true scale on the photograph" is untrue, since all lines parallel to this axis are lines of true scale. (He probably meant to state that this axis of tilt is the only line having the same scale as that of a truly vertical photograph taken from the same altitude.)

On p. 53, at top, the description of the figure on p. 52 states that "the small drawing . . . shows at the same scale as the profile above the amount and direction of the displacements. . . . " These should be at the same scale as the "photographic negative" at the top of the figure. There are actually neither in the same scale nor any other scale (they are not drawn in the same proportions). This error may or may not be in the text of the previous publication whose diagram the author used. (The diagram does, however, illustrate the points intended.)

I would differ from the author in a few minor matters of photographic interpretation. For instance, I would doubt (p. 72, top) that he saw the rails of the railroad track (Pl. 9), but rather suspect that he saw the two tracks of a double-track railroad. On p. 74, middle, the author states "a characteristic marshy area lies at 15," (Pl. 9), and on p. 76 "in the marshy area only differential grazing could have produced the rectangular pattern." The alleged marshy area has the normal pattern for an area of incipient "pimple mounds," whose darker places merely take longer to dry out after rains, but are dry most of the time. (The author could have used Plates 38 and 39 to point out typical marshy areas.) The remarkable dunes illustrated on p. 148 I believe to be an extremely well developed case of the longitudinal variety described and figured in Lobeck's *Geomorphology*, pp. 382–83. The author seriously considers several rather fantastic theories regarding these, relating them to topographic features at a distance, or structural features, and the explanation of Lobeck, the only one the photographic evidence will permit, is practically lost to the bewildered reader. The book gives no illustrations of typical sand dunes. The hypothesis of the fault on Fig. 41 (p. 140), and Pl. 26 (p. 142) must be seriously questioned, for when Pl. 26 is seen in three dimensions the top of the inner granite gorge appears to have the same height on either side of the tributary valleys at all points. A large joint, or fault having mainly horizontal movement could have been responsible for the tributaries' alignment.

The interpretation of culture (Ch. 4) is too incomplete and sketchy, and based on only one photograph; hence, many types of features, such as quarries, mines, industrial establishments, are not included or illustrated.

The reason for the curvature of the apparent horizon (p. 187) is not given, and this curvature in the diagram is exaggerated in such a way as to give the reader a false picture. Actually its departure from a straight line is insensible in the class of oblique photos described. The apparent horizon has a hyperbolic curve only on a photograph, and not in nature as the author's wording would imply. It is caused by the fact that every photograph is a "gnomonic projection," and the apparent horizon is not a great circle as is the true horizon. Only great circles (and straight lines) appear on photos as straight lines. The true shape of the hyperbola of the apparent horizon can be ascertained as follows. Get the value of the *CH* in angular measure (formula given on p. 186, again on p. 188), lay off this angle with the true horizon both to left and right at *H*, and below true horizon. These two lines so drawn form the limits of the two arms of the hyperbola passing through *C*.

If I might be permitted another possible aid to the student conscientiously trying to understand Eardley's book,—on p. 74, bottom, he is referred to Pl. 8 (p. 57) for an illustration of direct reflection of the sun from bodies of water. I doubt if one reader in a hundred will find this without help. The white spot next to the collimation mark on the south edge of the lowest photo is this reflection, and tiny white spots or dots may be picked up at the corresponding positions on the other two photos. Not mentioned by the author, but of equal interest, are the associated "light spots" (areas of no visible shadows) on a line joining the reflection spots and the center of the photographs, and extended an equal distance; hence seen in this case near the collimation marks at the top edge of each photo. The centers of these spots contain the shadow of the airplane if visible, and this will give the clue as to their relation with the sun. These light spots, not requiring water, are visible on practically all photos whereas the reflection spots are visible only when bodies of water

happen to lie at that part of the photo. (On most aerial photographs these two types of spots are not present at all, the sun not being high enough in the sky.) The whitened appearance of the two ponds in the middle photo which appear black in the lower photo is caused by reflections from the bottoms of the ponds. The large whitish area just below the center of the lowest photo without a counterpart on the middle photo is caused by reflection from a moist hillside sloping toward the south (sun) at the proper angle to give this reflection to the camera. (These photos were obviously taken very soon after a rain.)

Lastly, I wish to offer a criticism not at all reflecting upon the author, put possibly upon the publisher. The modernistic style of "bleeding" or trimming photos at the edge of the pages has robbed us of the scales on pp. 83, 102, 143, and others, and of the index on p. 198, and of lettered locations described in the text on p. 164. How much interesting and valuable photographic detail has been lost in many of the photographs from this regrettable practice, only the author can tell.

RECENT PUBLICATIONS

CALIFORNIA

*"Foraminifera from the Type Area of the Kreyenhagen Shale of California," by J. A. Cushman and S. S. Siegfus. *Trans. San Diego Soc. Nat. History*, Vol. 9, No. 34 (San Diego, October 1, 1942), pp. 385–426, Pls. 14–19, 1 diagram, 1 table.

*"Imperial Carbon Dioxide Gas Field," by Jas. C. Bransford. *California Oil World*, 1st issue (Los Angeles, July, 1942), pp. 13–14; reprinted in *California Jour. Mines and Geol.*, Vol. 38, No. 2 (San Francisco, April, 1942), pp. 198–201; 4 figs.

ENGLAND

*"The Middle Jurassic Rocks of Yorkshire: A Petrological and Palaeographical Study," by F. Smithson. *Quar. Jour. Geol. Soc. London*, Vol. 98, Pts. 1–2 (London, September 30, 1942), pp. 27–59; 15 figs.

GENERAL

*"Surface Energy Relationships in Petroleum Reservoirs," by H. K. Livingston. *Petrol. Tech.*, Vol. 5, No. 6 (November, 1942). 6 pp., 1 table. *A.I.M.E.T.P. 1526.*

*"Reservoir Analysis and Geologic Structure," by J. M. Bugbee. *Ibid.* 12 pp., 2 figs. *A.I.M.E.T.P. 1527.*

*"Effect of Casing Perforations on Well Productivity," by Morris Muskat. *Ibid.* 10 pp., 9 figs. *A.I.M.E.T.P. 1528.*

*"Analysis of Reservoir Performance," by R. E. Old, Jr. *Ibid.*, 13 pp., 6 figs., 1 table. *A.I.M.E.T.P. 1529.*

**Oil and Gas Field Development in United States, Year Book 1942 (Review of 1941)*, Vol. 12. 790 pp. Annual review for 1941 of geological and geophysical prospecting, land and leasing activities, wildcat exploration, proved field development, oil and gas production, pipe line and refinery statistics. Published by National Oil Scouts and Landmen's Association, Box 425, Austin, Texas. Price, $7.50.

Proc. 8th Amer. Sci. Congress, Vol. 4, Geological Sciences. 764 pp. Congress held in Washington, D. C., May 10–18, 1940, under auspices of the Government of the United States. 72 articles in English and Spanish grouped under 8 general subjects: (1) Paleozoic Formations and History, (2) Mesozoic and Tertiary Formations and History, (3) Mesozoic and Cenozoic Vertebrate Faunas and Floras, (4) Tectonics, Igneous History and Physiography, (5) General Geology, (6) Economic Geology-Petroleum, (7) Economic

Geology-Metalliferous Deposits, (8) Volcanology. Published by the Department of State, Washington, D. C.

Flush Production (The Epic of Oil in the Gulf-Southwest), by Gerald Forbes. 253 pp., Published by the University of Oklahoma Press, Norman, Oklahoma. Cloth. Price, $2.75.

Illustrated Catalogue of North American Devonian Fossils. Section 5B, "Conocardiidae," by C. C. Branson, 34 illus. cards. Section 9B, "Leperditacea," by A. S. Warthin, Jr., 19 illus. cards. Wagner Free Institute of Science, Philadelphia, Pennsylvania (November, 1942). Price, $2.85, plus carriage.

*"Development of the Northern Allegheny Synclinorium and Adjoining Regions," by G. Marshall Kay. *Bull. Geol. Soc. America*, Vol. 53, No. 11 (New York, November 1, 1942), pp. 1601–58; 11 figs.

*"Tertiary Prairie Grasses and Other Herbs from the High Plains," by Maxim K. Elias. *Geol. Soc. America Spec. Paper 41* (New York, November 25, 1942). 176 pp., 17 pls., 1 fig., 6 tables.

"Productivity of Oil Wells and Inherent Influence of Gas: Oil Ratios and Water Saturation," by R. V. Higgins. *U. S. Bur. Mines R. I. 3657* (Washington, D. C., October, 1942). 50 pp., 11 figs. Free.

Report of the Committee on the Measurement of Geologic Time, 1941–1942, by Alfred C. Lane, chairman, *et al.* National Research Council, 2101 Constitution Avenue, Washington, D. C. 64 pp. Price, $0.50.

KANSAS

*"Exploration for Oil and Gas in Western Kansas during 1941," by Walter A. Ver Wiebe. *State Geol. Survey Kansas Bull. 42* (Lawrence, June, 1942). 123 pp., 42 figs., 28 tables.

*"Late Paleozoic Pelecypods: Mytilacea," by Normal D. Newell. *State Geol. Survey Kansas*, Vol. 10, Pt. 2 (Lawrence, October, 1942). 115 pp., 22 figs., 15 pls.

*"Stratigraphy of the Pre-Greenhorn Cretaceous Beds of Kansas," by Norman Plummer and John F. Romary. *Ibid., Bull. 41* (November, 1942). 36 pp., 4 figs. 2 pls.

KENTUCKY

*"Kentucky's New Burbank Field Producing 8,000 Barrels Daily," by Willard Rouse Jillson. *Oil and Gas Jour.*, Vol. 41, No. 32 (Tulsa, December 17, 1942), pp. 18 and 77; 1 development map.

MISSISSIPPI

*"Tallahatchie County Mineral Resources," by Richard Randall Priddy and Thomas Edwin McCutcheon. *Mississippi Geol. Survey Bull. 50* (University, 1942). 157 pp., 15 figs., 2 pls. (geologic map of Tallahatchie County and regional structure map).

NEW YORK

*"The Brachiopoda of the High Point Sandstone of New York," by Merrill A. Stainbrook. *Amer. Jour. Sci.*, Vol. 240, No. 12 (New Haven, December, 1942), pp. 879–90; 2 pls.

PALESTINE

*"Geology of the Eastern Nazareth Mountains, Palestine. I. Cretaceous Stratigraphy," by Heinz A. Lowenstam. *Jour. Geol.*, Vol. 50, No. 7 (Chicago, October–November, 1942), pp. 813–45; 7 figs.

TEXAS

*"West Texas Barred Basin," by Robert I. Roth. *Bull. Geol. Soc. America*, Vol. 53, No. 11 (New York, November 1, 1942), pp. 1659–74; 2 pls., 3 figs.

WYOMING

*"Underground Water Resources of Chugwater Creek, Laramie River, and North Laramie River Valleys, Wyoming," by Acus R. Edwards. *Geol. Survey Wyoming Bull. 32* (Laramie, November, 1941). 32 pp., 3 figs., 3 pls.

*"Structure of the Elk Mountain District, Carbon County, Wyoming," by R. H. Beckwith. *Ibid., Bull. 33* (September, 1941). Reprinted from *Bull. Geol. Soc. America*, Vol. 52, pp. 1445–86; 1 fig., 2 pls.

THE BULLETIN

For 2 or 3 years prior to 1942 the *Bulletin* contained several hundred more pages of major articles per year than it contained in preceding years. Those unusually large issues were possible, without an increase in dues, because of the continued increase in Association members and *Bulletin* contributors. Beginning with the July, 1942, number, in anticipation of a definite transfer of our members from oil industry to military activity, and in view of extra financial demands during war time, the *Bulletin* is appearing in less voluminous issues. This course is believed wise for the conservation of Association resources, and adequate to meet the needs of *Bulletin* readers.

In order to maintain an ample supply of scientific articles, both majors and minors, and at the same time to meet governmental requests to economize in the use of paper stock, the *Bulletin* type page was made larger with the July issue. The line of type is longer and more lines are printed on each page, so that more of the blank marginal space is being put to use. Thus, each page now contains nearly 20 per cent more printed matter than it contained during the first 6 months of 1942, although the total number of pages is decreased. For the same reasons, 50-pound paper is being used instead of 60-pound stock, thus reducing the weight and volume of each edition. Transportation and storage requirements and other distribution expenses are also decreased. The *Bulletin* and, in fact, the Association as a whole, the individual members, and the headquarters employees are endeavoring to help to win the war.

10 per cent of A.A.P.G. investments are in War Bonds
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THE ASSOCIATION ROUND TABLE

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The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to the Executive Committee, Box 979, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

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Memorial

KENNETH ALLEN JOHNSTON

(1904–1942)

Kenneth Allen Johnston passed away at the California Hospital in Los Angeles, California, Friday, November 13, 1942, following an operation on October 26 for a perforated ulcer. For the past 16 years Mr. Johnston had had a constant struggle with ill health and his superior courage and gentleness of heart during all these years won for him the admiration and respect of all who knew him. Funeral services were conducted on November 16, 1942, at 2:00 P.M., at the Inglewood Park Cemetery in the Grace Chapel, after which

KENNETH ALLEN JOHNSTON

cremation followed and the ashes were placed at Forest Lawn Memorial Park, Glendale, California.

Mr. Johnston was born at Boulder, Colorado, on March 18, 1904, the only child of Daisy Allen Johnston and William Andrew Johnston, and grandson of Dr. Henry W. Allen, noted pioneer doctor in that part of the country. He received all his education in Boulder, graduating *cum laude*, major in geology from the University of Colorado in 1925. While attending the university he was active in the Geological Society and a charter member of the Delta Sigma Phi fraternity.

Upon his graduation he accepted a teaching fellowship at Washington University, St. Louis, and while there worked toward his master's degree.

In the spring of 1926, he accepted the position of assistant curator of the Colorado State Museum, but due to ill health had to resign in August, 1926, and undergo surgical treatment at the Mayo Clinic.

In March, 1927, he accepted a position as geologist and geophysicist for the Midwest Refining Company (Stanolind) and spent the next 2½ years in New Mexico and West Texas. Geophysical work in which he was engaged was instrumental in that company discovering the Hobbs, New Mexico, pool.

In September, 1928, he went to California to work for The Texas Company as a geologist and geophysicist, and later he joined the Geo. F. Getty interests, doing similar work throughout the states of California, New Mexico, and Texas.

For the past 7 years he was associated with the Buttes Oilfields, Inc., Oakland, California, as geologist, geophysicist and petroleum engineer, and was instrumental in locating the first commercial gas field in northern California. However, for the past 3 years his health was such that he was unable to devote much time and energy to the geological profession.

He was always a prolific reader and his intelligence and visionary outlook on world affairs together with his brilliance of wit endeared him to his friends and close associates.

Surviving him are his wife, the former Esther Alice Smith of Boulder, Colorado, a childhood friend and classmate at the University of Colorado, whom he married on September 12, 1925, now residing at 821 Green Avenue, Los Angeles, California, and his mother, Mrs. Daisy Allen Johnston of Phoenix, Arizona.

Mr. Johnston had been a member of the American Association of Petroleum Geologists since 1928.

STANLEY C. HEROLD

GLENDALE, CALIFORNIA
December, 1942

LEWIS SAMUEL CORYELL
(1894–1942)

Lewis Samuel Coryell was born, July 7, 1894, in Marine Mills, Washington County, Minnesota, a small hamlet situated on the beautiful St. Croix River. He passed away very suddenly on September 14, 1942, at Wichita Falls, Texas, as a result of a heart

LEWIS SAMUEL CORYELL

attack, and until the time of the fatal attack he appeared to be in the best of health. He is survived by his wife, Verre Farmer Coryell, a daughter, Gloria, a student at the University of Texas, a son, Jean, and two grandchildren, Bruce and Kathleen, of Galveston, Texas, and a brother, G. B. Coryell, Bristow, Oklahoma.

When Lewis was a young child his parents moved to Osceola, Wisconsin, where he attended public schools, graduating from high school in 1913. He then attended the University of Minnesota where, in 1917, he received the degree of Engineer of Mines in geology. He was a member of the Sigma Rho professional mining fraternity.

In 1917 he joined The Texas Company as field geologist in the Ranger district but this work was interrupted when he joined the United States Naval Air Force. He was one of the early naval pilots, and commissioned an ensign. While in the service he was a member of the Aero Club. In 1919 he returned to his chosen profession and during the next 9 years he was employed chiefly in Kansas and Oklahoma, by the New England Petroleum Company, Twin State Oil Company, Phillips Petroleum Company, and Philmack Oil Company. In 1928 he opened his office as consulting geologist in Bristow, Oklahoma, and from 1931 to 1935 he was retained by the Lima Oil and Gas Company. In 1937 he accepted a position as district geologist at Abilene, Texas, with the Indian Territory Illuminating Oil Company and was transferred to Midland, Texas, in 1939. When this company merged with the Cities Service Oil Company he was transferred to Wichita Falls, Texas, as district geologist for the north-central Texas area, which position he held at the time of his death.

Lewis was one of the early members of the American Association of Petroleum Geologists, being elected to membership in the Association in 1920. At the annual convention of the Association in Tulsa in 1924 he won the championship in golf, a sport which was his main hobby. He was a thirty-second degree Mason, a member of Zurah Temple, Minneapolis, Minnesota.

The untimely death of Lewis Coryell came as a severe shock to his many friends and the absence of his cheery smile, hearty laugh, and firm handclasp will be missed by all who were favored by his acquaintance and friendship. He was an able geologist, a real friend, a devoted husband, and a kind father. His friendly disposition was sincere and genuine and he always displayed the same thoughtfulness in his home as in his dealings with his fellow men. It was a great privilege to have known him intimately.

CLINTON ENGSTRAND

WICHITA FALLS, TEXAS
December 1, 1942

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AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

Convention headquarters for the twenty-eighth annual meeting of the Association, April 7–9, 1943, is the Hotel Texas, Fort Worth, Texas.

ROBERT E. KING, geologist with the Shell Oil Company, Inc., Midland, Texas, has resigned to join the Superior Oil Company of California, Roswell, New Mexico.

C. L. MOHR, geologist for the Ambassador Oil Corporation, Fort Worth, Texas, has resigned to join the United Geophysical Company, Pasadena, California, for work in Chile.

ALLEN C. TESTER has been granted leave of absence from Iowa University in order to enter the armed forces of the United States. He has entered service as a captain in the Corps of Engineers.

J. VOLNEY LEWIS is senior industrial specialist in the mining division of the War Production Board, having transferred from the metals and minerals branch of the Bureau of Foreign and Domestic Commerce. His address is 1400 Somerset Place N. W., Washington, D. C.

JACK FRANCIS HARANG is an ensign in the U.S.N.R., temporarily stationed at Tucson, Arizona.

A. G. MCCARVER has left the Baroid Well Logging Service to join the geological staff of the Plymouth Oil Company, Midland, Texas.

New officers of the Kansas Geological Society, Wichita, are: president, E. P. PHILBRICK, Magnolia Petroleum Company; vice-president, DONALD B. WINES, N. Appleman and Company; secretary-treasurer, GLEN C. WOOLLEY, Transwestern Oil Company.

J. BASIL PRESTON is with the Corps of Engineers at Fort Belvoir, Virginia.

E. H. TOLLEFSON reported for active duty in the U.S.N.R. on December 22, appointed to the rank of Lieutenant.

JOHN M. LOVEJOY, president of the Seaboard Oil Company of Delaware, is chairman of the Petroleum Industry War Council committee to study the industry's war manpower problems.

J. DAVID LOVE resigned his position as research geologist for Shell Oil Company, Inc. to become assistant geologist for the U. S. Geological Survey. He is now in Afton, Wyoming, studying strategic war metals in the Rocky Mountain region.

Officers of the Rocky Mountain Association of Petroleum Geologists elected for the ensuing year are: president, RALPH D. COPLEY, The California Company; 1st vice-president, C. E. ERDMANN, U. S. Geological Survey; 2d vice-president, JOHN E. BLIXT, The Texas Company; secretary-treasurer, ROBERT E. SPRATT, U. S. Geological Survey, 208 Custom House, all of Denver.

SUMNER T. PIKE, of the Securities and Exchange Commission, Philadelphia, is special petroleum adviser to Leon Henderson, director of the Office of Price Administration, Washington, D. C.

C. R. McCOLLOM, consulting geologist, has closed his Los Angeles office, and may be addressed at 875 Bellefontaine Place, Pasadena, California. He is with Photogrammetric Instruments, Inc., a branch of Fairchild Aerial Surveys, making instruments for the Army Air Corps, as liasion officer and other administrative work.

R. KEITH MILLER, recently employed in the land department of the Shell Oil Company, Ind., died at his home in Centralia, Illinois, December 18.

RALPH W. IMLAY spoke before the South Texas Geological Society, San Antonio, December 11, on "Jurassic Correlations in Southern Arkansas, Northern Louisiana, Northern Mexico, and Cuba," and before the Shreveport, Louisiana, Geological Society, December 16, on "Jurassic Formations of the Gulf Region."

Lieutenant CHESTER D. WHORTON may now be addressed at Amphibious Force-Administrative Command, Naval Operating Base, Nancemond Hotel, Norfolk, Virginia. He is attached to the Intelligence Department, Aerial Photographic Interpretation.

The Shawnee Geological Society elected officers for 1943 as follows: president, GRANT W. SPANGLER, Stanolind Oil and Gas Company; vice-president, EDWIN A. DAWSON, consulting geologist; secretary-treasurer, MARCELLE MOUSLEY, Atlantic Refining Company.

Newly elected officers of the North Texas Geological Society are: president, EARL M. STILLEY, consulting geologist; vice-president, CLINTON ENGSTRAND, Shell Oil Company, Inc.; secretary-treasurer, DAN D. HENINGER, The Ohio Oil Company, 615 Hamilton Building, all of Wichita Falls, Texas.

The University of Michigan announces a 1-year curriculum for women students in petroleum geology, beginning February 4, 1943. During the following 12 months, those enrolled in this curriculum will be given as much academic work in geology as a student preparing for the profession ordinarily obtains in 4½ years. During 12 weeks in the summer of 1943 the group will be moved to Camp Davis, Jackson Hole, Wyoming, for field work in geology and instruction and practice in geological drafting. Prerequisites for admission to this concentrated program include 1 year's work in physical and historical geology, trigonometry, and a B-grade average. Upon successful completion of the curriculum a certificate will be issued. Full credit, which can be counted toward a degree, will be given for all courses taken. The purpose of this curriculum is to supply the oil companies with replacements during the remaining war years for their geological staffs. The feasibility of the plan has been discussed with men in the industry. Men classified in 4F but physically able to do field work are also eligible for this program. Further information can be obtained by writing to Professor K. K. Landes, Department of Geology, University of Michigan, Ann Arbor, Michigan.

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Meetings: First and third Wednesdays of each month from October to May, inclusive, at 7:30 P.M., Edwards Hotel, Jackson, Mississippi. Visiting geologists welcome to all meetings.

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Meetings: Technical program each month, subject to call by Program Committee, Oklahoma City University, 24th Street and Blackwelder. Luncheons: Every Thursday, at 12:00 noon, Skirvin Hotel Coffee Shop.

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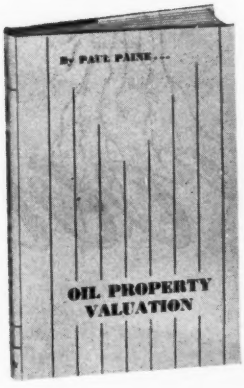

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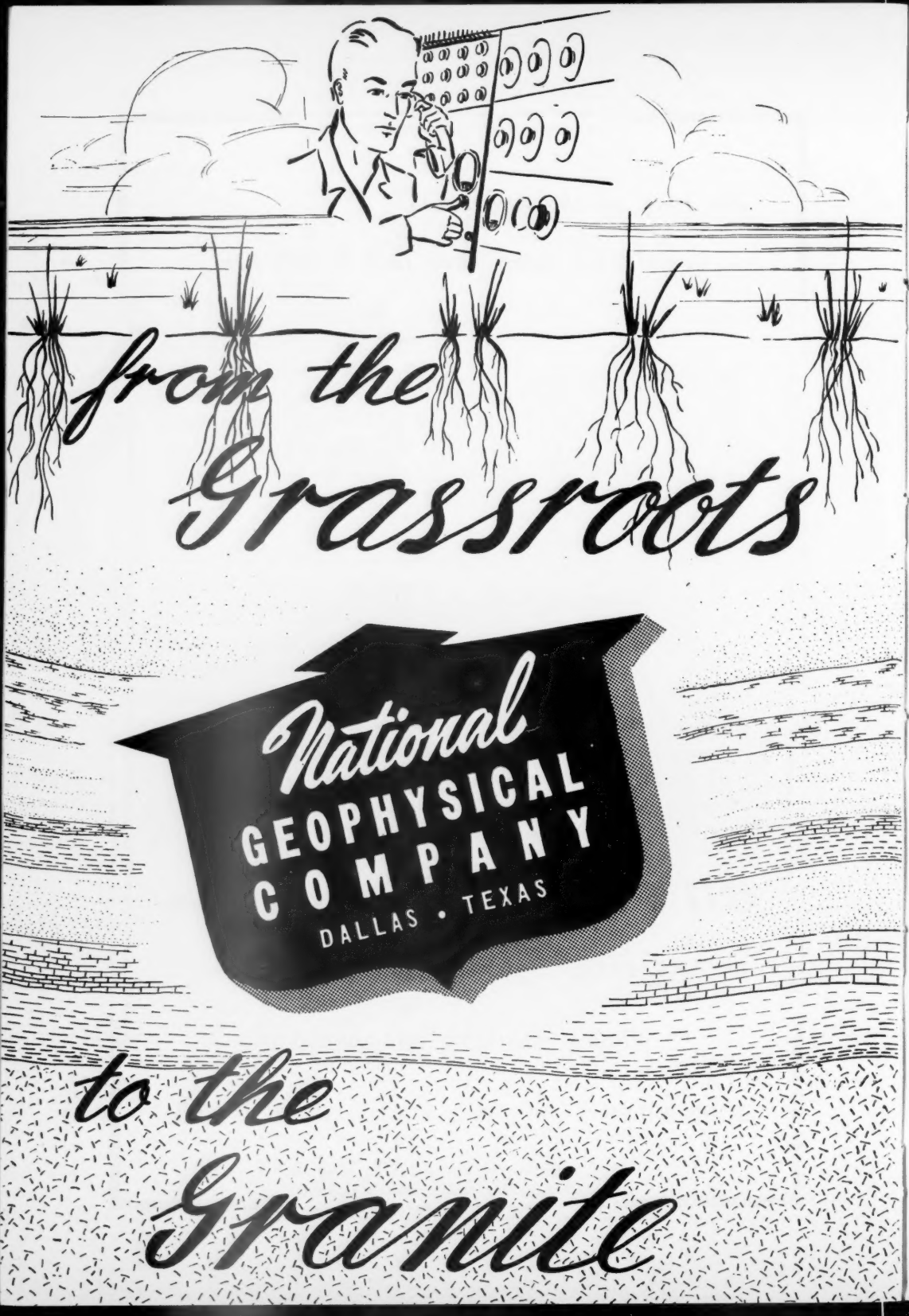
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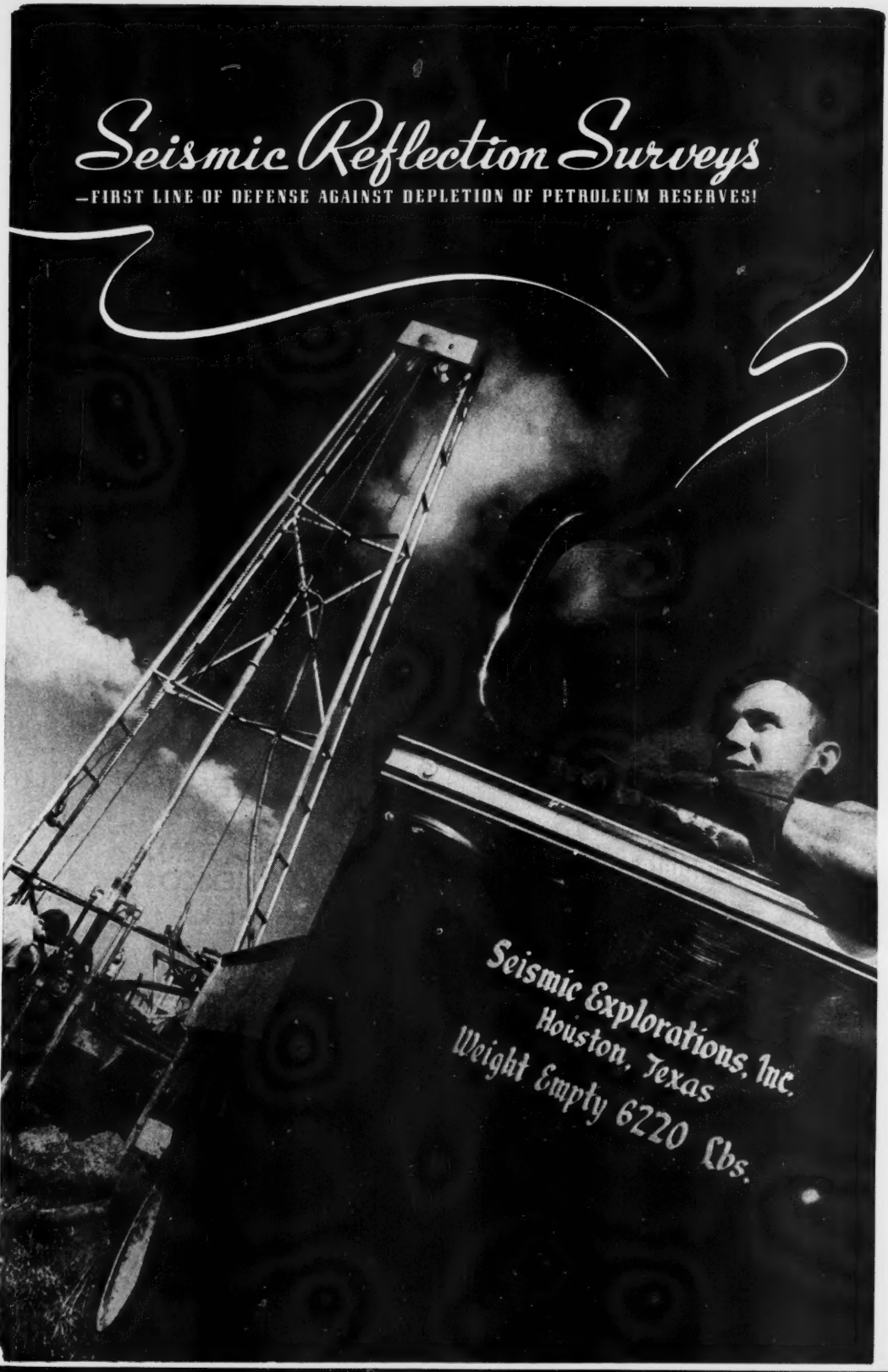
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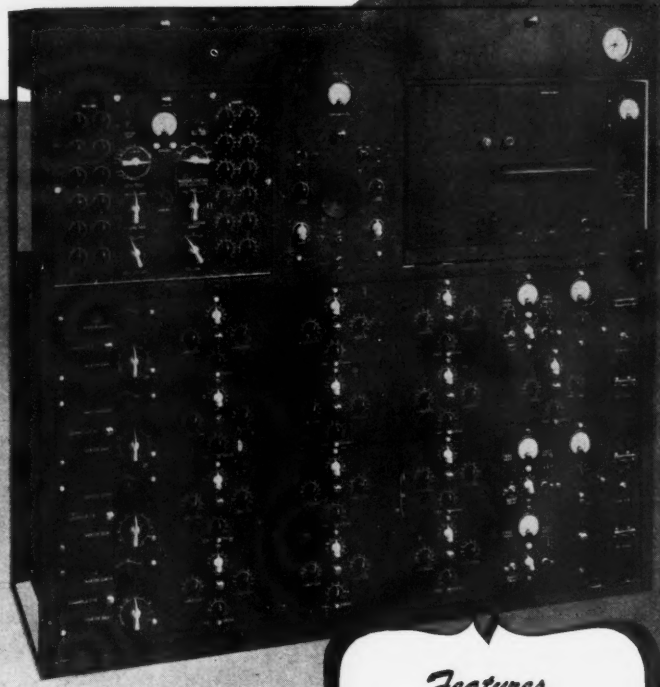

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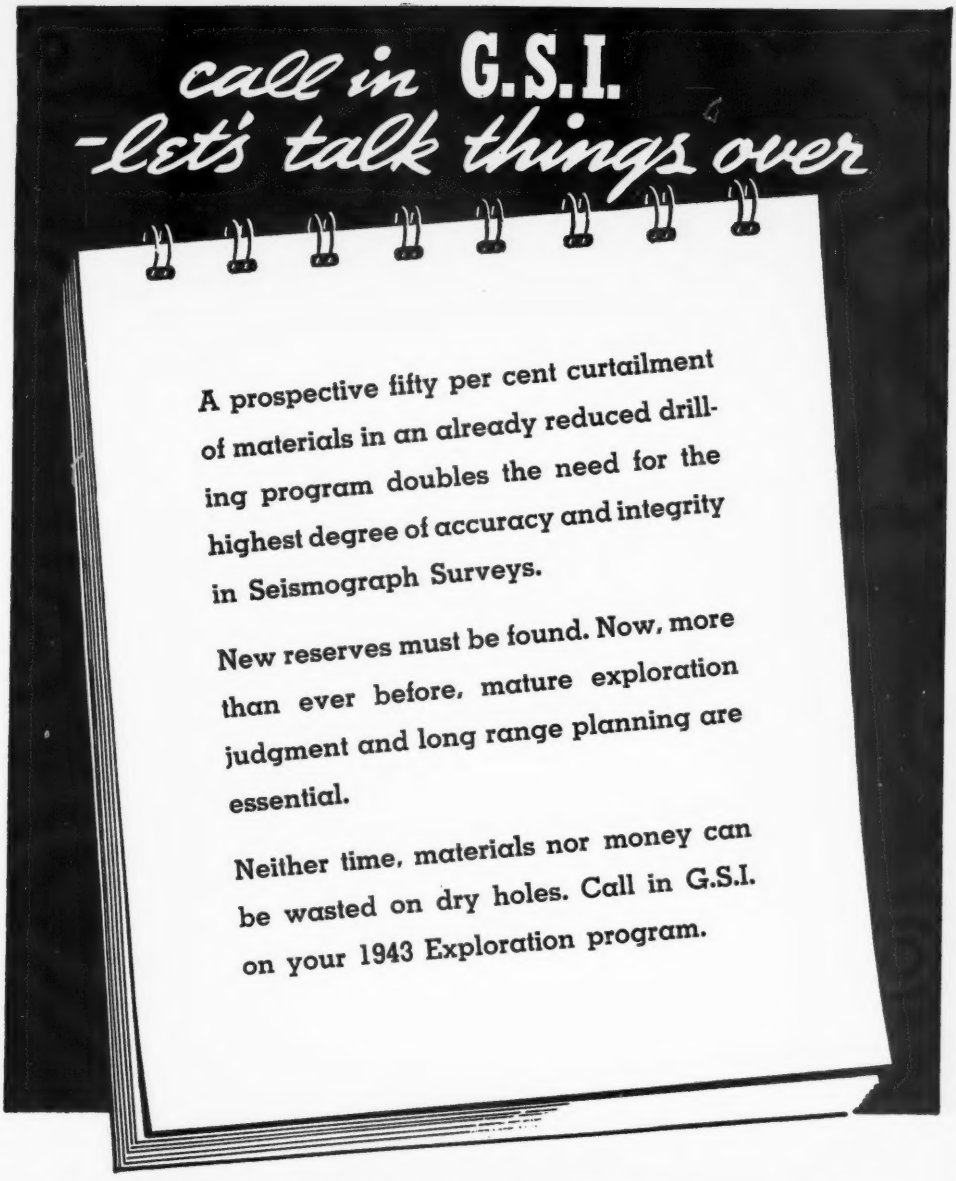
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